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FATE OF SELECTED METALS AND EMISSIONS FROM A SLUDGE/WASTEPAPER GASIFIER

by

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16. ABSTRACT

A study was conducted to quantify a pilot-scale sludge and wastepaper gasification system for its gaseous, particulate and metal emissions. The gasifier produced up to 1800 MJ/hr using a fuel mixture of source-separated wastepaper and sludge.

Emissions varied between 15.1 and 16.5 ppm for CO, 1.39 and 12.7 ppm for hydrocarbons, 98.6 and 121 ppm for NO_x, and 55.5 and 105 ppm for SO_2. Particulate concentrations varied between 35.70 and 192.96 mg/dry standard cubic meter corrected to 12 percent CO_2.

Metals balance data indicated that Cd, Pb, and Zn increased in concentration (compared to the fuel) in gaseous material leaving the gasifier and that Cu, Cr, and Fe increased in concentration (compared to the fuel) in the char-ashes leaving the gasifier.

The particulate emissions in the burned gas from the gasifier were less than the allowable limits for solid waste incineration.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxics Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

Development of safe and economical methods for disposing of the sludges produced from wastewater treatment operations is one of the most pressing environmental needs. This publication provides much needed information on the feasibility of one approach to dispose of sludge and municipal solid wastes. The process also generates a gas that can be used to reduce the need for priority fuels.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

A study was conducted to analyze a pilot-scale gasification system for sludge and wastepaper and to quantify its gaseous, particulate, and metal emissions. The downdraft, packed-bed, air-blown gasifier processed up to 1800 MJ/hr and used four different densified mixtures of wastewater sludge and source-separated wastepaper as a fuel. Eight experimental gasifier runs were conducted to quantify operation characteristics. In addition, particle and metal size distributions, and particulate, gaseous, and metal emissions were measured from the combustion of producer gas, a product of the gasification process.

Producer gas energy contents varied between 4.83 and 7.04 MJ/m^3, with the lowest values associated with the highest fuel ash contents. Measured concentrations of gaseous emissions varied between 15.1 and 16.5 ppm for CO, 1.39 and 12.7 ppm for total hydrocarbons, 98.6 and 121 ppm for NO_x, and 55.5 and 105 ppm for SO_2. Particle concentrations varied between 35.70 and 192.96 mg/dry standard cubic meter corrected to 12 percent CO_2.

Based on metals balance data, volatile metals like Cd, Pb, and Zn are enriched on particulate matter, and the matrix metals like Cu, Cr, and Fe are enriched in the char. Particle and metal size distribution data showed that the mass median aerodynamic diameter for particulate matter varied between 0.31 and 0.95 μm. These data also indicated that Cd, Pb, and Zn were enriched on smaller particles and that Ni, Cr, and Fe were enriched on larger particles.

This report was submitted in fulfillment of Cooperative Agreement No. R-809747 by the University of California, Davis, California, under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period December 1, 1982 to May 31, 1984, and work was completed as of December 1984.

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METRIC CONVERSION TABLE

English Unit	Metric Equivalent	Conversion Factor
Pound (lb)	Kilogram (kg)	0.4536
Short Ton (ton)	Metric Ton (m. ton)	0.9072
Cubic Feet (ft^3)	Cubic Meter (m^3)	0.0283
Gallon (U.S.) (gal)	Liter (ℓ)	3.785
British Thermal Unit (Btu)	Joule (J)	1055
Fahrenheit (°F)	Centigrade (°C)	5/9 (°F - 32)

SYMBOLS/ABBREVIATIONS

Symbol	Definition
ppmv	unit per million volume
µm	micron (micrometer)
XRF	x-ray fluorescence
AAS	atomic absorption spectrophotometry

SECTION 1

INTRODUCTION

The adverse environmental impacts of wastewater sludge on both groundwater and land quality is a growing concern. As a result, incinerators and other thermal devices for neutralizing wastewater sludge will be used to a greater extent in the future. Though high-temperature processing of wastewater sludge effectively destroys most pathogens and toxics, concern exists about atmospheric discharges of particulate matter, metals, and gaseous emissions from thermal devices. The purpose of this report is to analyze a pilot-scale thermal gasification system for sludge and wastepaper and to quantify the gaseous, particulate, and metal emissions.

The sludge and wastepaper gasification process discussed here involves the gasification of densified mixtures of sludge and source-separated wastepaper in a simple packed-bed reactor using air as the oxidant. A combustible gas rich in carbon monoxide and hydrogen was produced by the gasifier and combusted in an incinerator. This report represents a continuing development of the sludge and wastepaper gasification process originally reported by Vigil et al. (38) and Sorbo et al. (33).

THE GASIFICATION PROCESS

Gasification is an energy efficient technique used to produce low-energy gas and reduce the volume of the fuel. The gasification process involves the partial combustion of a carbonaceous fuel to generate a combustible gas rich in carbon monoxide, hydrogen, and some saturated hydrocarbon gases, principally methane. A brief review of the gasification process is given here.

Definition

Gasification involves the partial combustion of a carbonaceous fuel to generate a combustible gas containing carbon monoxide, hydrogen, and gaseous hydrocarbons. Currently much confusion exists in the literature between the terms "pyrolysis" and "gasification." This report uses the following definitions given by Lewis (24):

> Pyrolysis - Thermal proccessing of waste in the absence of oxygen in a) indirectly heated retorts, and b) furnaces that are directly heated by fuel gases from a burner firing on a stoichiometric air/fuel ratio.

Gasification - Thermal processing of waste in which a fraction of the stoichiometric oxygen required by the waste is admitted directly into the fuel bed to liberate the heat required for endothermic gasification reactions. The volatile portion of incoming waste will be pyrolyzed by the heat of the fuel gases, and the outlet gas composition will reflect both processes.

Historical Development

Gasifiers have been used since the 19th century. The first coal gasifiers were built by Bischof in Germany in 1839, by Ebelman in France in 1840, and by Ekman in Sweden in 1845. This early development was followed by the Siemens brothers in Germany in 1861. The Siemans' gasifiers were used primarily to fuel heavy industrial furnaces. The development of cooling and cleaning equipment by Dowson in England in 1881 extended the use of gasifiers to small furnaces and gas engines (29).

By the early 1900's, gasifier technology had advanced enough that most ligno-cellulosic materials such as wood, fruit pits, straw, and walnut shells could be gasified. These early gasifiers were used primarily to provide fuel for stationary gasoline engines. Portable gasifiers also emerged in the early 1900's. They were used for ships, automobiles, trucks, and tractors. The real impetus for the development of portable gasifier technology was World War II. During the war years, France had more than 60,000 charcoal-burning cars, and Sweden had about 75,000 wood-burning, gasifier-equipped buses, cars, tractors, and engine-powered boats. With the return of relatively cheap and plentiful gasoline and diesel oil after the end of World War II, gasifier technology was all but forgotten. In Sweden, however, research has continued into the use of wood-fueled gasifiers for diesel tractors and transport trucks. (28). Furthermore, the downdraft gasification of peat is being pursued actively in Finland (17).

Solid waste gasification systems have not been as succesful as systems using charcoal, coal, wood, or certain agricultural wastes as fuels. The principal causes for the failure of solid waste gasification technology have been the complexity of the systems and a lack of appreciation for the difficulties involved in gasifying a heterogeneous fuel like solid waste. The approach taken in this project was to use a very simple reactor (a vertical packed-bed, downdraft gasifier) with the cleanest form of solid waste (source-separated wastepaper) mixed with lagoon-dried wastewater sludge. A review of research into pyrolysis and gasification systems of solid wastes is presented by Jones (19) and Jones et al. (20).

Reactor Types

The four basic types of reactors used in gasification are: 1) vertical packed-bed, 2) multiple hearth, 3) rotary kiln, and 4) fluidized bed. The vertical, packed-bed, downdraft reactor has a number of advantages over the other types, including simplicity and relatively low capital cost. But it is more sensitive to the mechanical characteristics of the fuel. The merits and limitations of vertical packed-bed gasifiers are discussed in detail by Eggan and Kraatz (8).

In a downdraft gasifier, fuel flow is by gravity, with air and fuel moving co-currently through the reactor (see Figure 1). At steady state, four zones form in the reactor. In the hearth zone, where air is injected radially into the reactor, partial combustion reactions predominate. Some heat transfers from this zone upward into the fuel mass, causing pyrolysis reactions in the distillation zone and partial drying of the fuel in the drying zone. Actual production of the fuel gas occurs principally in the reduction zone (below the hearth zone), where endothermic reactions predominate, forming CO and H_2. The hot carbon bed in the combustion zone and upper part of the reduction zone thermally cracks many of the higher hydrocarbons, producing methane and other non-condensible hydrocarbon gases. The end products of the process are a carbon-rich char and the producer gas.

Gasification Reactions

A gasifier is basically an incinerator operating under reducing conditions. During the gasification process, five principal reactions occur:

$$C + O_2 \quad = \quad CO_2 + 393.8 \text{ MJ/kg-mol} \qquad \text{exothermic}$$

$$C + H_2O \quad = \quad CO + H_2 - 131.4 \text{ MJ/kg-mol} \qquad \text{endothermic}$$

$$C + CO_2 \quad = \quad 2CO - 172.6 \text{ MJ/kg-mol} \qquad \text{endothermic}$$

$$C + 2H_2 \quad = \quad CH_4 + 75.0 \text{ MJ/kg-mol} \qquad \text{exothermic}$$

$$CO + H_2O \quad = \quad CO_2 + H_2 + 41.2 \text{ MJ/kg-mol} \qquad \text{exothermic}$$

The heats of reaction shown above are evaluated at $25^{o}C$ and 1 atmosphere of pressure. The heat to sustain the process is derived from the exothermic reactions, whereas the combustible components of the producer gas are primarily generated by the endothermic reactions. Although the reaction kinetics of the gasification process are quite complex, the operation of air-blown, downdraft gasifiers of the type used in this research is straightforward. More detailed discussions of gasification theory and reaction kinetics are available in Gumz (14), Hoffman (15), Rambush (29), and Reed (30).

Downdraft Gasifier Constraints

Although downdraft gasifiers are very simple reactors, they have exacting fuel requirements dealing with moisture content, particle size, and ash content. Excessive moisture in sludge and wastepaper fuels can be overcome by drying the fuel before gasification. The upper limit of fuel moisture content for downdraft gasifier fuels is about 20 percent.

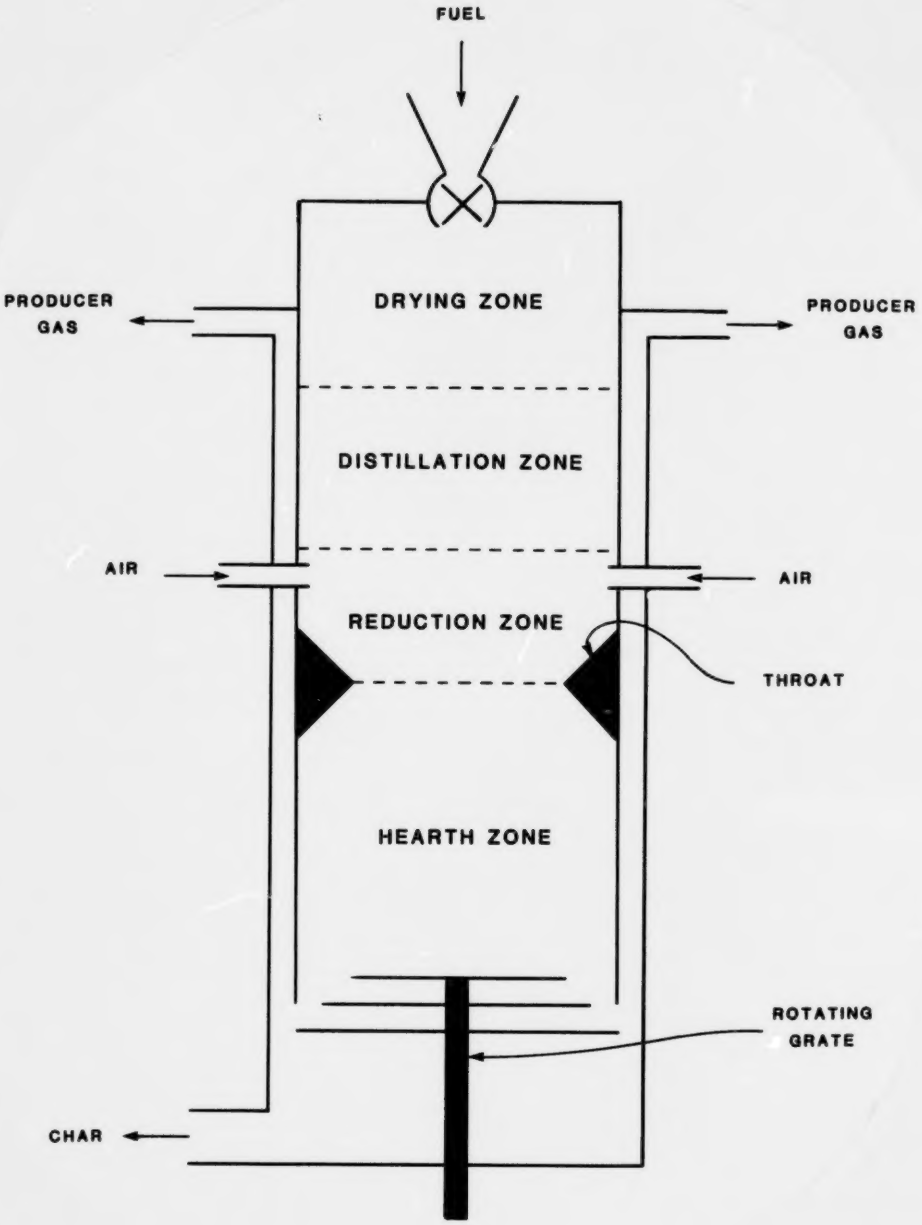
FUEL
PRODUCER GAS
DRYING ZONE
PRODUCER GAS
DISTILLATION ZONE
AIR
AIR
REDUCTION ZONE
THROAT
HEARTH ZONE
ROTATING GRATE
CHAR

Figure 1. Schematic of a downdraft gasifier.

Because the fuel flow in a downdraft gasifier is by gravity, the fuel must be dense particles of uniform size. The fuel particles must be of uniform size to prevent mechanical bridging. An agricultural cuber can be used to produce a sludge/wastepaper fuel of sufficient density and size uniformity.

The fuel ash content plays an important role in downdraft gasifiers. In addition to lowering the energy content of the fuel, fuel ash forms slag upon reaching its melting point in the gasifier and then cooling. Excessive slag formations in downdraft gasifiers can block the flow of fuel and char through the gasifier and thus halt the gasification process. From a sludge disposal point of view, it would be ideal to gasify pure sludge. But because the ash content of wastewater sludge is 25-40%, gasification of pure sludge in a downdraft gasifier is not feasible. (The maximum feasible fuel ash content for standard downdraft gasifiers is about 5-7%.) Sludge can be gasified in a downdraft gasifier by mixing it with appropriate quantities of source separated wastepaper (ash content of about 3%) to achieve an acceptable overall fuel ash content.

SLUDGE AND WASTEPAPER GASIFICATION FOR SMALL COMMUNITIES

To dispose of wastepaper and sludge in small communities, a sludge and wastepaper gasification system was first proposed by Vigil (37). A downdraft gasifier located at the wastepaper treatment plant is used to gasify a densified mixture of sludge and wastepaper, resulting in the production of a low-energy gas (producer gas) and char. The chemical energy in the producer gas is converted into electricity with an engine (or gas turbine) generator set. The electricity produced is either used in the treatment plant or sold to the local power utility.

The collection of source-separated wastepaper is one of the most important aspects of a small community sludge and wastepaper gasification system. The source separation system is designed to collect wastepaper and other recyclables efficiently without the use of large, capital-intensive, mixed-waste recovery systems. Though source separation systems are ideally suited to resource recovery in small communities, many large communities also use source separation systems.

For many years, it has been assumed that the recycling of wastepaper for the manufacture of low-quality paper insulation or other products is both economically and ecologically sound. But the high cost of energy coupled with the fluctuating markets for wastepaper are making energy recovery from wastepaper an attractive option.

In many cases, only selected, clean newsprint is suitable for recycling purposes. Source-separated wastepaper may be used more effectively in a sludge/wastepaper gasification system for the production of energy than in a wastepaper recycling system for the production of low-grade paper. Because the wastepaper recycling requirements are less restrictive when applied to a sludge/wastepaper gasification system, a larger fraction of the solid waste generated in the community may be used.

SECTION 2

CONCLUSIONS

Eight experimental gasifier runs were conducted using a downdraft gasifier system fueled with four densified fuels. Conclusions derived from the most significant results of this work are presented below.

1. Four different mixtures of sludge and wastepaper were gasified with fuel ash contents varying between 3.1% and 9.5%. The fuel mixture with the highest fuel ash content that did not cause significant slag formations is considered to be the maximum feasible fuel ash content. For these tests, the maximum feasible fuel ash content was 6.9%.

2. The producer gas generated during eight gasifier runs had an energy content that varied between 4.83 and 7.04 MJ/m^3 (dry, LHV, 25^oC). The lowest producer gas energy contents are associated with high fuel ash contents.

3. The cold gas efficiency of the gasifier varied between 52.35% and 84.58%, but because of experimental errors, efficiencies above 75% should be considered suspect.

4. Particle emission tests were conducted during six of the gasifier runs. Particle concentration values varied between 35.70 and 192.96 mg/ dry standard cubic meter (DSCM) (corrected for 12% CO_2). Gaseous emission tests were conducted for three gasifier runs. The measured concentrations varied between 15.1 and 16.8 ppmv for CO, 1.39 and 12.7 ppmv for THC, 98.6 and 121 ppmv for NO_x, and 55.5 and 105 ppmv for SO_2.

5. A metals balance was performed on the gasification process. Concentrations of seven metals (cadmium, lead, zinc, nickel, copper, chromium, and iron) were measured in the gasifier process streams (fuel, char, fly ash, slag, particle emissions). Because relatively large concentrations of cadmium, lead, and zinc were found in the emissions, they are considered volatile and likely to be enriched on small particulate matter in the emissions. Copper, chromium, and iron were found to be nonvolatile elements, associated principally with the ash matrix. Because the nickel closure data are sporadic, it is not possible to classify nickel either as a nonvolatile matrix element or as a volatile element.

6. The results of an x-ray fluorescence (XRF) analysis and atomic absorption spectrophotometry (AAS) were compared for Run 33 samples. Though XRF produced elemental concentration data from many elements for a single trial, the AAS results were more accurate than the XRF results.

7. Particle and metal size distribution data were generated during Runs 40, 41, and 42. Cadmium, lead, and zinc concentrations were enriched on smaller particles, and nickel, chromium, and iron were enriched on larger particles. These results are consistent with vapor pressure data for these metals. Based on the data, copper behaves as a volatile metal, an observation that is not consistent with vapor pressure data.

SECTION 3

EXPERIMENTAL APPARATUS, METHODS, AND PROCEDURES

The experimental work described in this report is divided into three parts: 1) the experimental gasifier runs dealing with the design, operation, and analysis of the gasification system, 2) air pollution emission studies dealing with gaseous, particulate, and metal emissions from the gasifier system, and 3) the analysis of samples for metals. Most of the experimental work described in this report was conducted on the University of California, Davis, campus using the facilities, shops, and laboratories of the Departments of Civil and Agricultural Engineering, and the Crocker Nuclear Laboratory. Some air pollution studies were conducted using the facilities and personnel of the California Air Resources Board in Sacramento.

EXPERIMENTAL GASIFIER RUNS

To analyze the behavior of the gasification of densified mixtures of sludge and wastepaper, and to measure particulate, gaseous, and metals emissions, eight experimental gasifier runs were conducted. A description of the experimental gasification system, the laboratory testing, the field testing, the preparation of gasifier fuels, operational procedures, and mass and energy balance procedures follows.

Experimental Gasification System

The pilot-scale gasification system used in this project consists of three parts: 1) batch-fed, downdraft gasifier, 2) data acquisition, and 3) producer gas burner. A schematic diagram of the sludge/wastepaper gasification system developed for this project is shown in Figure 2.

Batch-Fed Downdraft Gasifier - A pilot-scale, batch-fed downdraft gasifier was designed and constructed for the experiments and is shown in Figure 3. The gasifier is built in three main assemblies: fuel hopper, firebox, and char pit. The fuel hopper is a double-walled cylinder. The inner wall is in the form of a truncated cone to reduce the tendency for fuel bridging. The double wall acts as a condenser to remove water vapor from the fuel before gasification. Condensed vapor is collected in a condensate gutter and drained off after each run. The fuel hopper is mounted on the firebox with quick-release clamps to allow for easy inspection after experimental runs. Because of the need for extended run lengths, a fuel hopper extension was added to the original fuel hopper. The fuel hopper extension, consisting of a circular cylinder 40.6 cm in diameter and 121.9 cm in length, is bolted to the original fuel hopper.

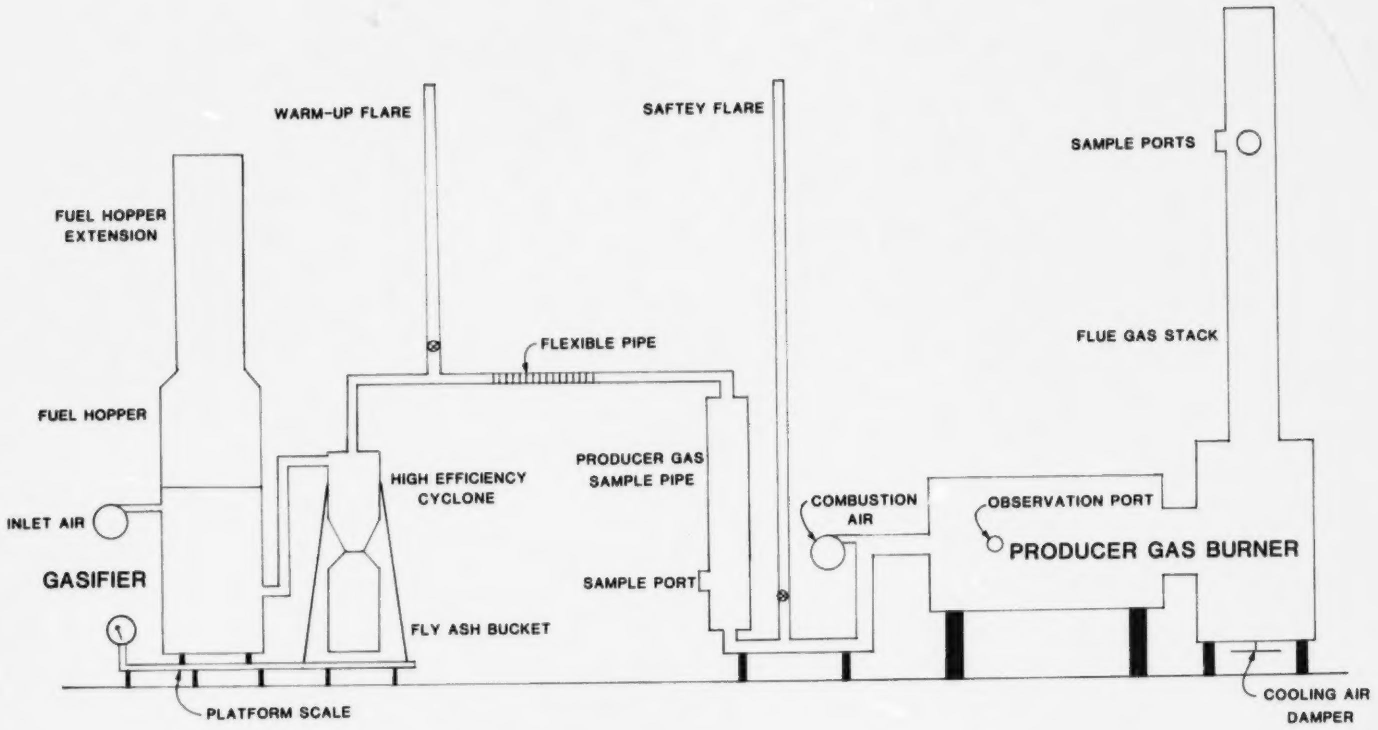
WARM-UP FLARE
SAFTEY FLARE
SAMPLE PORTS
FUEL HOPPER EXTENSION
FLEXIBLE PIPE
FLUE GAS STACK
FUEL HOPPER
PRODUCER GAS SAMPLE PIPE
HIGH EFFICIENCY CYCLONE
COMBUSTION AIR
OBSERVATION PORT
INLET AIR
PRODUCER GAS BURNER
GASIFIER
SAMPLE PORT
FLY ASH BUCKET
PLATFORM SCALE
COOLING AIR DAMPER

Figure 2. Schematic diagram of the UCD sludge/wastepaper gasification system.

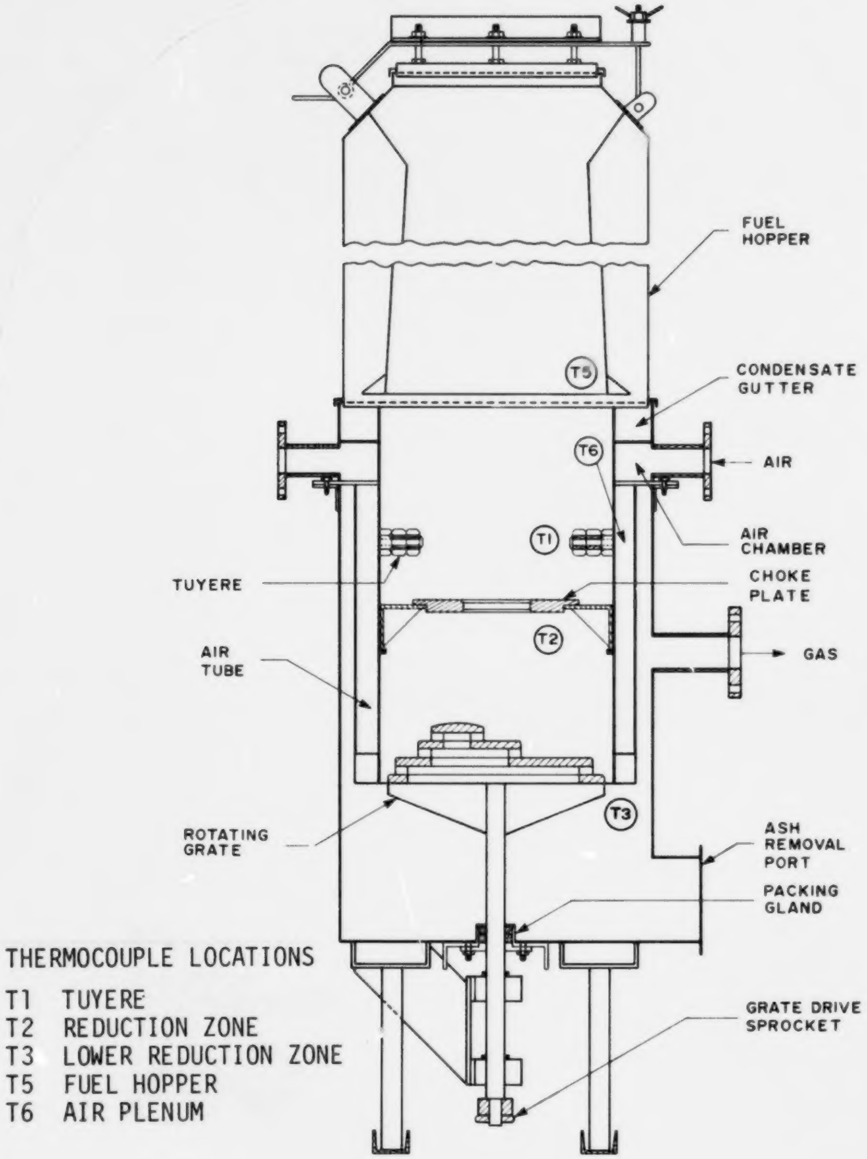
FUEL HOPPER
CONDENSATE GUTTER
AIR
AIR CHAMBER
CHOKE PLATE
TUYERE
GAS
AIR TUBE
ROTATING GRATE
ASH REMOVAL PORT
PACKING GLAND
GRATE DRIVE SPROCKET
T1
T2
T3
T5
T6
THERMOCOUPLE LOCATIONS
T1 TUYERE
T2 REDUCTION ZONE
T3 LOWER REDUCTION ZONE
T5 FUEL HOPPER
T6 AIR PLENUM

Figure 3. Cross-section - UCD sludge/wastepaper gasifier.

The firebox is also a double walled cylinder. The inner cylinder is the actual firebox. Air is supplied by four air tubes to the annular space between the walls, which acts as an air plenum to distribute air evenly to the six tuyeres (air nozzles) that supply air for partial combustion of the fuel. The choke plate acts as a large orifice, replacing the venturi section previously used in earlier World War II and Swedish gasifier designs. The firebox assembly is flange mounted to the char pit.

A rotating eccentric grate is located in the char pit immediately below the choke plate. The grate supports the fuel bed and allows passage of char and gas into the char pit.

Char particles that pass through the grate, fall into the char pit where they are scraped into an auger through an opening in the bottom of the char pit, by a wiper blade attached to the grate shaft. The char particles are conveyed by an auger from the char pit to the char bin, where they are collected during the run. To eliminate the potential for explosions in the char bin, air is purged from the char bin with nitrogen gas prior to the run. Producer gas is drawn off continuously through four ports (only one port shown in Figure 3) on the outer wall of the firebox, and passed through a producer gas manifold to the cyclone. The outer wall of the fire box, the producer gas manifold, and the cyclone are insulated.

Little information is available in the literature concerning the geometric design of a gasifier. The only detailed work on the subject is contained in the report by Nordstrom (28). Empirical relationships presented by Nordstrom (28) were used to estimate the relative sizes of the choke plate orifice diameter, tuyere diameter, tuyere length, and distance between the tuyeres and choke plate. Because the tuyeres, choke plate, and choke support plate and hoop are removable, the internal geometry can be changed easily. A diagram showing the internal dimensions of the gasifier is shown in Figure 4 and Table 1.

The choke plates and tuyeres were constructed from Type 304 stainless steel. A temperature resistant alloy, ASTM Type A515 was used for the firebox and the rotating grate. The remainder of the gasifier was constructed from Type 1040 mild steel.

The high efficiency cyclone was designed and constructed to remove particles greater than 10 microns from the producer gas stream. The design follows a Stairmand design (34) with a body diameter of 17.8 cm.

Data Acquisition - Temperature, pressure, and producer gas analysis data were collected for each gasifier run. Two different acquisition systems were used to collect gasifier temperature and pressure data. The Civil Engineering (CE) data acquisition system, developed by Vigil (38) consists of a Digitec Model 1000 Datalogger for temperature monitoring, and various pressure gauges and inclined manometers for pressure monitoring. The datalogger is used to record the channel number, temperature, and elapsed time.

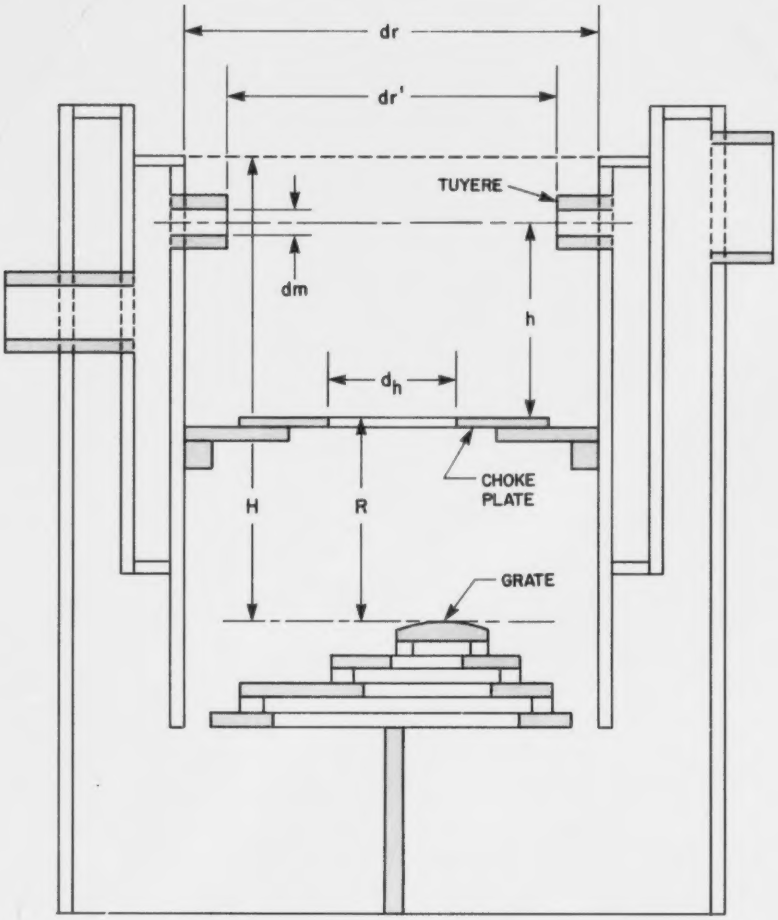
dr
dr'
TUYERE
dm
h
d_h
CHOKE PLATE
H
R
GRATE

Figure 4. Interior dimension symbols for a downdraft gasifier firebox.

Table 1

INTERNAL DIMENSIONS OF UCD CIVIL ENGINEERING SLUDGE/WASTEPAPER GASIFIER

Dimension	Symbol	Length (cm)
Firebox diameter	dr	45.7
Tuyere circle diameter	dr'	32.0
Tuyere diameter	dm	1.7
Choke plate orifice diameter	dh	17.8
Tuyere - choke plate distance	h	11.4
Choke plate - grate distance	R	21.0
Overall firebox length	H	80.6

These data are printed in paper tape at five minute intervals. The CE data acquisition system was used to monitor temperature and pressure data for Runs 33, 36, 37, 38, and 44.

A data acquisition system developed by the Department of Agriculture Engineering at UC Davis was used to monitor temperature and pressure data for Runs 40, 41, and 42 and producer gas analysis data for all runs. A brief description of the UCD Agricultural Engineering Data Acquisition System is found in Appendix C.

The sample train shown in Figure 5 was used to measure the producer gas composition. The producer gas analyzer system is made up of four separate instruments: 1) Leeds and Northrup Model 7865 Multi-component infrared/thermal conductivity analyzer. The infrared analyzer was used for CO and Co_2 determinations while the thermal conductivity analyzer determined H_2, 2) Leeds and Northrup Model 7863 Thermomagnetic Oxygen Analyzer, and 3) Beckman Model 400 flame ionization hydrocarbon analyzer for CH_4. The percent by volume of dry producer gas at ambient temperature was determined for CO, CO_2, O_2, H_2, and total hydrocarbons while the percentage of N_2 was obtained by difference. Prior to each gasifier run, the producer gas analyzer was recalibrated using a series of calibration gases. The calibration gases were prepared by Scott-Marrin, Inc., of Riverside, CA. and are traceable to NBS Standard Reference Materials. A list of the calibration gases and their constituents is shown in Table 2. The accuracy of the gas analysis system is as follows: $O_2 = 0.125\%$ meter readout, $CO\text{-}CO_2\text{-}H_2 = 0.5\%$ meter readout, THC = 0.1% meter readout. The producer gas moisture content was determined by measuring the weight change of the condensor and molecular sieve module (see Figure 5), and recording the volume through the dry gas meter. Producer gas moisture content values represent an average over the entire run which the producer gas could be combusted so that gaseous and particulate analyses of the producer gas combustion products can be obtained. A photograph of the producer gas burner system is shown in Figure 6. Two important features of the producer gas burner are:

1. Producer gas burner and furnace were designed to provide a gas residence time of 1 second at 1093°C at a gasification rate of 90.7 kg/hr. Temperatures from thermocouples located at the producer gas inlet to the furnace, inside the furnace, and at the flue gas outlet are recorded continuously with a digital datalogger.
2. Flue gas stack whose length is 10 stack diameters (diameter = 45.7 cm). Two 10.2 cm diameter sample ports are located eight pipe diameters downstream and two pipe diamters upstream of any flow disturbance. The fule gas stack dimensions comply with EPA's particulate and velocity sampling criteria (26).

Laboratory Testing

Ultimate analysis and energy content of fuel, char, and fly ash samples were tested in the laboratory. Ultimate analysis of dry (overnight) fuel, char, and fly ash samples for carbon (C), hydrogen (H), oxygen (O), nitrogen

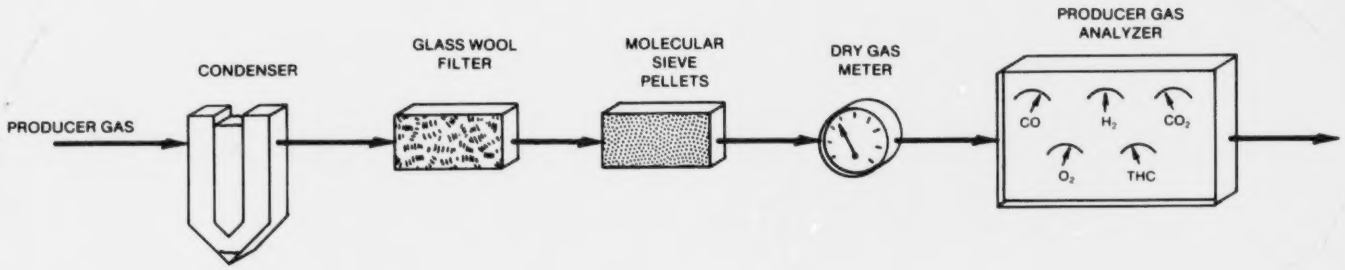
PRODUCER GAS
CONDENSER
GLASS WOOL FILTER
MOLECULAR SIEVE PELLETS
DRY GAS METER
PRODUCER GAS ANALYZER
CO
H_2
CO_2
O_2
THC

Figure 5. Producer gas analysis system train.

Table 2

CALIBRATION GASES USED FOR THE UCD PRODUCER GAS ANALYSIS SYSTEM

Cylinder No.	Concentration (V/V), %					
	CO	H_2	CH_4	CO_2	O_2	N_2
CC 222	32.3 ± 0.3	21.7 ± 0.2	10.0 ± 0.1	--	--	balance
CC 626A	31.5 ± 0.3	--	1.034 ± 0.01	--	--	balance
CC 368	--	--	--	23.6 ± 0.06	4.17 ± 0.04	balance
CC 249	--	--	--	6.43 ± 0.06	0.503 ± 0.01	balance
CC 622A	16.29 ± 0.16	2.05 ± 0.02	--	--	--	balance

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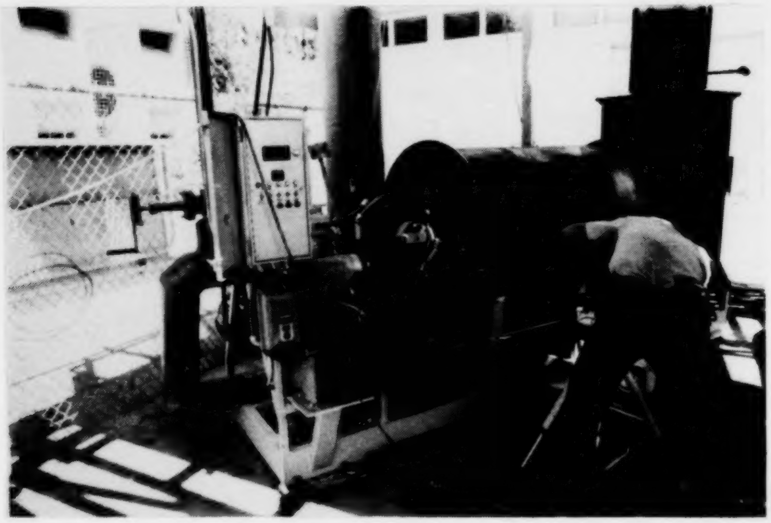

Figure 6. Producer gas burner system.

(N), sulfur (S), and residue was conducted by the Micro-Analytical Laboratory, Chemistry Department, University of California, Berkeley campus. Percent C, H, and N were analyzed with a Perkin-Elmer Gas Analyzer. The percent S was measured by Grote combustion method (ppt with $BaSO_4$). The percent residue was measured by weighing the ash resulting from the C, H, and N analysis. The percent O was found by difference. The residue determination results in complete oxidation of all inorganic elements in the sample. Because the char and fly ash are formed under reducing conditions in the gasifier, the inorganic elements may not be completely oxidized. As a result, the residue determination can add mass (oxygen) to the true residue fraction in the char and fly ash by the oxidation process. Thus, the fraction of oxygen in the char and fly ash samples can be lower than the true values.

The energy content of the fuel, char, and fly ash was determined with a Parr Oxygen Bomb Calorimeter according to ASTM D 2015-66, "Gross Calorific Value of Solid Fuel by the Adiabatic Bomb Calorimeter". The moisture content of fuel was determined by measuring the weight change of about 1 kg of fuel, dried to a constant weight at $105^{0}C$. The moisture content of the char and fly ash was determined for Run 33 and found to be negligible.

The preparation of fuel, char, and fly ash samples for ultimate analysis and energy content determination is discussed in the next section.

Field Testing

The following data were collected in the field during each gasifier run.

Temperature - Gasification process temperatures in the following locations were measured at 5 minute intervals during Runs 33, 36, 37, and 38 using the CE data acquisition system and at 1 minute intervals during Runs 40, 41, 42, and 44 using the AE data acquisition system: air inlet, air plenum (see Figure 3), reduction zone (see Figure 3), lower reduction zone (see Figure 3), fuel hopper (see Figure 3), gas outlet, furnace inlet, and furnace outlet.

Air Flow - Air flow was measured by measuring the static pressure and the pressure drop across a standard flange mounted orifice plate. Static pressure and pressure drop readings were recorded automatically using the AE data acquisition system during Runs 40, 41, and 42 and manually during all other runs. The orifice plate was calibrated periodically using a portable venturi meter.

Fuel Consumed - The fuel consumed during a run was determined by subtracting the weight of the fuel remaining in an "empty gasifier" at the end of the run from the weight of the fuel added to the gasifier during the run. An "empty gasifier" level is defined to be at the top of the fire box (see Figure 4).

Char and Fly Ash Produced - Char and fly ash produced was removed from the gasifier and weighed on the day following the run after the gasifier had cooled.

Pressure Drop - The pressure drop across the gasifier and the high efficiency cyclone were measured automatically every minute during Runs 40, 41, and 42 and manually every 5 minutes during all other gasifier runs.

Slag - To assess the potential for sludge/wastepaper cubes to cause slagging, the gasifier was partially disassembled after each run, and the residual char in the firebox removed and sifted for slag agglomerations. The quantity and location of the slag agglomerations were noted.

Bulk Density - Fuel bulk density was determined during each gasifier run and char bulk density was determined after each gasifier run.

Preparation of Gasifier Fuels

Four different mixtures of sludge and wastepaper were densified in a modified agricultural cuber and used as fuel for this project. Lagoon dried sludge was obtained from the UCD wastewater treatment plant and trucked to the Papakube densification facility in San Diego. Recycled newspaper was purchased in San Diego and used as the source of wastepaper. Pre-weighed mixtures of sludge (wet) and wastepaper (wet) were mixed together with a hammer mill and conveyed to the densifier. The densified fuel cubes produced had a square cross-section(2.7 cm x 2.7 cm)and a variable length (3 to 9 cm). The physical and chemical characteristics of the fuels are described in Section 4.

Operational Procedures

The following operating protocol for each gasifier run was used.

1. "Empty" Gasifier - The gasifier was defined to be "empty" when fuel was added to the top of the fire box. It is necessary to define an "empty" gasifier to calculate a mass balance.

2. Fill Gasifier - The fuel hopper was filled and the weight of the fuel added was recorded.

3. Ignite Gasifier Fuel - A heated probe was inserted into the gasifier ignition port until smoke emerged from the port.

4. Turn on Gasification Air and Ignite Gas - The desired air flowrate as measured with an air inlet orifice was set by a blower bypass valve. A propane torch was used to ignite the producer gas from the flare stack.

5. Warm-up Period - It is necessary to warm-up the gasifier before

representative data can be taken. Therefore the gasifier was warmed up for 90 minutes, at a specified air inlet rate, before data were taken. At the completion of the warm-up period fuel was added. Because it was impossible to determine the fuel used and the char and fly ash generated during the warm-up period, warm-up runs were conducted for each fuel mixture. During the warm-up runs (one for each fuel mixture) the gasifier was operated for 90 minutes at the specified air inlet rate. The fuel consumed, and the char and fly ash generated during the warm-up run were subtracted from the fuel consumed, and the char and fly ash generated during the gasifier run. Thus net fuel, char, and fly ash rates of the gasifier at "steady state conditions" are obtained.

6. Record Data - Air pressure drop, air static pressure, gasifier pressure drop, gasifier static pressure, cyclone pressure drop, cyclone static pressure, dry producer gas composition, and various process temperatures were taken at one or five minute intervals.

7. Grate Rotation - The grate was operated at a rate sufficient to maintain a pressure drop across the gasifier of about 13 cm of H_2O. Operation of the grate causes the displacement of char into the char pit and reduced the pressure drop across the gasifier.

8. Producer Gas Moisture Content - The producer gas moisture content was determined over the entire run length by the condensation method described earlier.

9. Refueling - A thermocouple in the fuel hopper was used to monitor the fuel level. A rapid rise in the fuel hopper was an indication of an empty fuel hopper. When the fuel hopper temperature rose rapidly, the inlet air was shut off. The fuel hopper lid was opened, the fuel added was weighed, and the fuel hopper lid was closed. The refueling procedure took about 3 minutes.

10. Shut Down - The blower was turned off.

On the day following the completion of each gasifier run the standarized procedure outlined below was followed:

1. Unload Char - Char was removed from the char bin and the weight and bulk density were recorded. Char samples were taken.

2. Unload Fly Ash - Fly ash was removed from the fly ash bucket and weighed. Fly ash samples were taken.

3. Gasifier Teardown - The fuel hopper was removed. Any fuel remaining above the "empty gasifier" level (top of the firebox) was removed and weighed. If the fuel level was below the "empty gasifier" level, fuel was added up to the "empty gasifier" level and weighed.

Then all fuel and char were removed from the gasifier and the interior of the gasifier was checked. The fuel and char were weighed and samples were saved for analysis. Then char was loaded into the gasifier up to the level of the tuyeres, fuel was added up to the "empty gasifier" level, and the fuel hopper replaced.

Mass and Energy Balance Computations

To aid in the analysis of the gasification process, mass and energy balances on seven gasifier runs were calculated. A complete discussion of the method of computation is found in Appendix A.

AIR POLLUTION EMISSIONS

Gaseous and particulate emissions from the combustion of producer gas generated from sludge/wastepaper fuels were determined. Particulate emissions were determined for Runs 36, 37, 38, 40, 41, 42 using EPA Reference Method 5 (22). Measurement of gaseous emissions using California Air Resources Board (CARB) Method 100 (35) was done during Runs 36,, 37, 38. CARB Method 100 is applicable for determining emissions of oxides of nitrogen, carbon monoxide, carbon dioxide, sulfur dioxide, total hydrocarbons, and oxygen from stationary source flowing gas streams in ducts, stocks, and flues except for turbine engines and stationary diesel engines. CARB Method 100 is an alternative method to EPA methods 3, 6, 7, and 10.

METALS BALANCE AND METALS EMISSIONS

The experimental methods, apparatus, and procedures used in performing a metals balance on the gasification system and determining the metals emissions are presented below.

Sampling and Sample Preparation

Due to the non-homogeneous nature of the sludge/wastepaper fuel, it was assumed that the char would also be non-homogeneous with respect to the metal fraction. Thus considerable effort went into gathering representative samples without metal contamination. The methods used to obtain representative samples of fuel, char, fly ash, slag, and particulate emissions are presented. Bomb calorimeter and ultimate analysis of fuel, char, and fly ash samples were also obtained using the methods described below.

Fuel - Preliminary work to determine the metals fractions in thirty individual fuel cubes was conducted. The procedure consisted of ashing the fuel cubes (750°C), HCl digestion of the residue, and Atomic Absorption Spectroscopy (AAS) analysis of the solution. The result yielded metals fractions with standard deviations greater than 50%. Because of the large standard deviation and the difficulty in analyzing 30 fuel cubes each run, this sample preparation method was deemed inappropriate.

To reduce the number of samples and still obtain the correct metals fraction in the fuel, a large number of cubes (10 kg, 200 cubes) was homogenized using a hammer mill. During each gasifier run, a random fuel sample of 10 kg was collected in a plastic bag, stored in the laboratory, and mixed and ground in the hammer mill. After grinding, 5 samples of approximately 5 g each were used for the determination of the metals content. This sample preparation technique yielded metals content standard deviations of 10 percent, based on 7 samples.

Due to the large standard deviations from metals analysis of individual char particles, it was decided to homogenize a large sample to reduce the number of samples to be analyzed for metals. A hand powered grinding mill was used to grind approximately 2 kg of char to a 4 mesh. This was then mixed well by hand in a plastic bag, from which 100 g was taken for fine grinding. The fine grinding was in a roller mill using a carborundum jar and grinding medium. The finely ground material was on the order of 10 microns in diameter. From the finely ground char, 3 samples of 1 gram each were used for the metals determination.

Slag - Because the quantity of slag was small, the entire sample (.5 to 2 kg) was crushed in the hand mill and mixed by hand. Approximately 100 g was placed in the roller mill for fine grinding. Three samples of 1 g each were used for the metals analysis.

Fly Ash - All of the fly ash collected in the cyclone was placed in a plastic bag and mixed by hand. A 100 g sample of the fly ash was finely ground in the roller mill. Three samples of 1 g each were taken for metals analysis.

Sludge and Wastepaper - The sludge used for this study was taken from the UCD sludge drying bed. It is anaerobically digested activated sludge. The sludge used for metals analysis was a random grab sample from the sludge used in the fuel cubes. Roughly 2 kg of sludge was coarsely ground with the hand mill and mixed by hand. Then a 100 g sample was placed in the roller mill and finely ground. Metal extraction and determination was performed on 3 oven dried samples of 1 g each.

The wastepaper was a random grab sample from the recycled newspaper used to make the fuel cubes. Approximately 100 g wastepaper was shredded in a high speed shearing micro-mill and analyzed for metals.

Metals Emissions - To quantify the metals emissions from the producer gas burner, particulate and condensed metals samples were collected using an EPA Method 5 test apparatus discussed earlier.

The Method 5 tests were conducted using a glass liner for the nozzle and filter holder to prevent metal contamination. The filters were 1.0 micron Zeflour teflon filters. All the Method 5 tests were conducted for 64 minutes from two ports. After the test all portions of the Method 5 apparatus that contacted the flue gas were washed with acetone and analyzed for metals. Runs 36, 37 and 38 the liquid collected in the condenser train was not tested for metals content. For Runs 40, 41 and 42 100 ml of 3N HCl was placed in the first impinger of the condenser train to capture any metals attached to sub-micron particles.

X-Ray Fluorescence Sample Preparation - X-ray fluorescence (XRF) was used to analyze gasifier samples from Run 33. The XRF samples were prepared in the Civil Engineering laboratory and sent to the Crocker Nuclear Laboratory (UCD) for analysis.

Mylar was used as the medium on which the fuel, char, fly ash, and slag samples were placed. Mylar was attached to a mounting slide which was designed for the XRF analyzer. The XRF sample preparation was done in three steps:

1. Weigh mylar and slide to 0.1 mg.

2. Using the nebulizer shown in Figure 7 attach sample to mylar. The nebulizer shown in Figure 7 consists of two 400 ml nalgene bottles fitted with slide mount holder, a sampler reservoir, and vacuum and pressurized air hoses. The mylar slide is placed in the slide mount holder of a clean nebulizer. The sample is placed in the sample reservoir and the nebulizer is sealed. After a vacuum has been applied for 30 seconds, the presurized air is turned on to suspend sample in air. The vacuum draws the suspended sample particles across the mylar. Because this has an adhesive coating on it, the sample particles stick to the mylar. The air and vacuum hoses are closed 5 seconds after sample particles appear in the vacuum hose. The mylar slide is removed from nebulizer.

3. The mylar slide with sample is weighed to the nearest 0.1 mg.

Laboratory Protocol

In the determination of trace quantities of heavy metals, it is critical to properly clean all glassware and plasticware to prevent sample contamination. In the metal extraction methods that follow, all water is distilled-deionized water from a glass still. In this report, Nalgene means glassware or Nalgene that has been cleaned with soap, rinsed with tap water, rinsed with deionized water, soaked in 5% V/V HCl for at least 2 hours, rinsed with distilled-deionized water and dried in an oven at 50 C. All clean glassware was stored with parafilm covering any openings and the Nalgene bottles were stored with their caps on. The glass pipets were cleaned by drawing three volumes of 5% V/V HCl, three volumes of distilled water, and then drying. The Nalgene pipets used were soaked overnight in 5% V/V HCl and rinsed with distilled water. Because HF can etch glassware, any sample containing hydrofluoric acid was placed in a Nalgene bottle. Commercially available 48% (w/w) hydrofluoric acid, 37% (w/w) hydrochloric acid, and boric

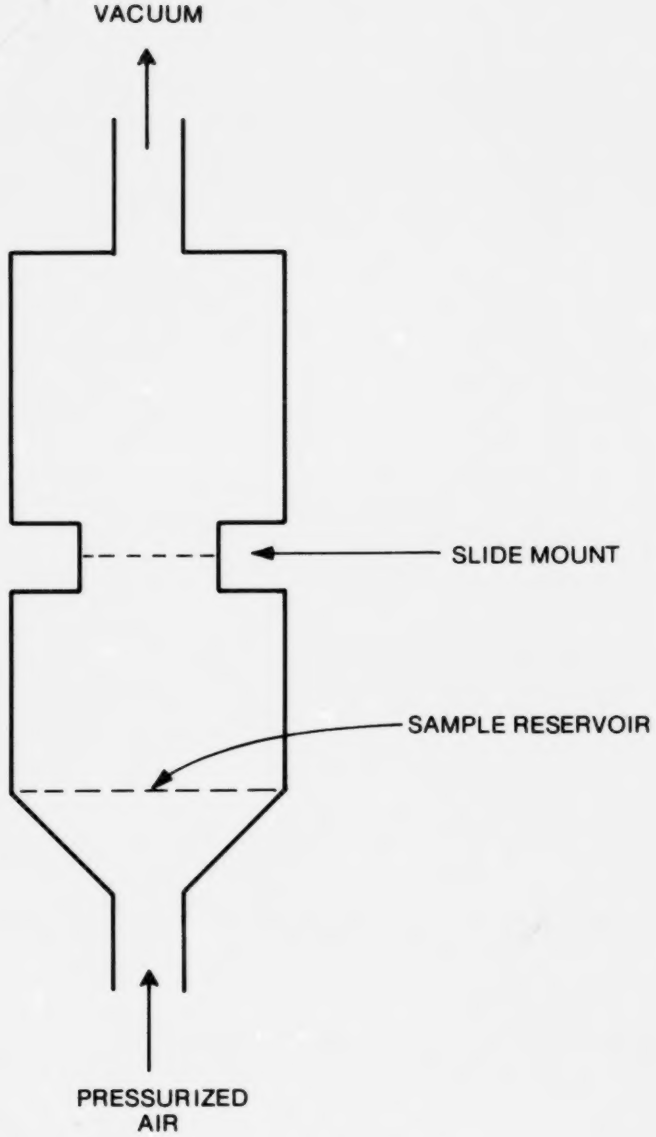
VACUUM
SLIDE MOUNT
SAMPLE RESERVOIR
PRESSURIZED
AIR

Figure 7. Nebulizer used to mount samples for XRF analysis.

acid were of reagent grade. Procedural blanks containing all reagents were carried through all steps of the dissolution process.

Metals Extraction

Extraction methods used in the metals analysis of fuel, sludge, wastepaper, char, fly ash, slag, particulate emissions samples, and impactor substrates are discussed below.

Fuel, Sludge, and Wastepaper - The fuel, sludge, and wastepaper were digested using the same method. Three 5 g samples of each fuel type were ashed in a muffle furnace at 200°C for 8 hours to drive off carbon and reduce the volume of the sample. Each sample was placed in a 125 ml Nalgene bottle (with screw caps) along with 5 ml of distilled water and 20 ml of concentrated HCl. The samples were then shaken a minimum of 8 hours on a platform shaker at low speed and room temperature. The samples were then filtered and washed with distilled water using a 4.0 micron Nuclepore polycarbonate filter, a plastic filter holder, and funnel (Nuclepore). The filtrate was collected in a clean 125 ml Nalgene bottle and saved to be combined with the filtrate of the second extraction.

The second phase of the metal extraction began by drying the filter residues overnight at 70°C. The filter residues were then ashed in porcelain crucibles at 600°C for 8 hours to drive off any remaining carbon, and cooled in a dessicator. The filter ash was then placed back in the Nalgene bottles. Care was taken to wash all the ash into the bottle with distilled water. 10 ml of concentrated HCl and 10 ml of concentrated HF were added to the ash and water. The bottles were then placed on the shaker for at least 8 hours. After shaking, 4 g of Boric Acid (H_3BO_3) was added and the bottles were shaken again for at least 4 hours or until the Boric Acid dissolved. If there was still ash that had failed to dissolve, the sample was filtered using the same filtering apparatus with the filtrate being combined with the first filtrate. Usually, all the ash was dissolved and the filtrates of the second dissolution and the first dissolution were combined. All the combined solutions were diluted to a final volume of 200 ml using Nalgene volumetric flasks. The samples were then analyzed for metals using AAS by the procedures outlined in the Analytical Methods section of this chapter.

Char, Fly Ash and Slag - The digestion method used with the char, fly ash and slag samples is very similar to the extraction method used with the fuel, paper and sludge. The difference between the two methods in the elimination of the initial low temperature ashing and the addition of HF during the first extraction to dissolve any metals bound by silicates before the high temperature ashing.

Each sample was placed in a 125 ml Nalgene bottle and wet with 5 ml of distilled water. 10 ml of concentrated HCl was added and the sample was shaken for 8 hours. After the 8 hours, 10 ml of concentrated HF was added and the sample was shaken overnight. The sample was then filtered using the 4.0

µm Nuclepore filters and filtering apparatus. As with the fuel, the filtrate was collected in a 125 ml Nalgene bottle. The filter residue was ashed at 600°C cooled in a dessicator and placed back in the Nalgene bottles used in the first dissolution. 10 ml of concentrated HCl and 10 ml of concentrated HF were added and the samples shaken at least 8 hours. After shaking all the ash was usually in solution. If any ash was not dissolved the sample was filtered and the filtrate combined with the filtrate of the first dissolution. If all the ash dissolved, the second dissolution filtrate was combined directly with the first dissolution filtrate. 8 g of Boric Acid was added to each of the combined filtrates and the samples were shaken for at least 4 hours to dissolve the Boric Acid. All samples were then diluted to a final volume of 200 ml with water.

Particle Emissions - Particle emissions from the combustion of producer gas were collected by the EPA Method 5, using 1.0 m Zefluor filters. The Method 5 probe was glass and the nozzle was stainless steel. The probe wash and the filter holder wash were in acetone, which was evaporated before the dissolution of the metals for AAS. To evaporate the acetone samples rapidly under the fume hood without sample contamination, the following procedure was followed. The samples were placed in a hot water bath at 50°C. The caps were removed and filtered air was fed into the bottles using a glass Pasteur pipette so that each bottle had an upward flux of air. The net flux of air out of the bottle reduced the possibility of the sample being contaminated by a small particle falling into the bottle. After the acetone was evaporated the residue was dissolved with 0.2 N HCl (5 ml HCl + 45 ml H_2O) to a final volume of 50 ml.

The Zeflour filters were carefully cut into pieces that could fit into a 250 ml flask. The filter pieces were placed in the flask without losing any particles. The filler pieces were digested for 30 minutes in 100 ml of concentrated HCl over low heat. The HCl was decanted and the filter pieces extracted 3 times with 20 ml of H_2O. The water extracts were combined with the HCl extract and evaporated to dryness. Redissolution of the residues was carried out with 10 ml of HCl, 10 drops of HNO_3 and 40 ml of water. The final volume of the sample was 50 ml.

The impinger catches of Runs 40, 41 and 42 were evaporated at 70°C in a 250 ml Ehrlenmeyer flask and redissolved with 50 ml of 0.5 M HCl.

Impactor Substrates - Particulate matter collected on the impactor substrates was analyzed for metals using AAS. After the mass of the loaded substrates was determined, the loaded substrates were placed in acid washed test tubes. A mixture of 25 ml HCl and 25 ml distilled H_2O was put in the test tube. The test tube was heated at 80°C for 30 minutes. The cooled acid solution was analyzed by AAS without filtration.

Quantitative Analysis of Metals

Two methods were used to determine the quantities of metals in each sample. The primary method was Atomic Absorption Spectroscopy (AAS), which was used to determine the concentrations of the various metals in each extraction. The secondary method was x-ray flourescence (XRF), which was used to verify the AAS, results of Run 33. Due to difficulties in sample preparation, XRF analysis was not used for samples from subsequent gasifier runs.

Atomic Absorption Spectroscopy - All AAS work was conducted using a Perkin-Elmer Model 2380 Atomic Absorption Spectrophotometer and an air-acetylene flame. Standards were prepared following the procedures outlined in Reference 1. Instrumental operating parameters of each metal are presented in Table 3. All stock solutions (1 mg/ml) were prepared once in an acidic solution (distilled H_2O + HNO_3) and stored at 4°C in 500 ml Nalgene bottles with the exception of the Cu and Cd stocks, which were purchased from Mallinckrodt. Standards were made by diluting the stock solution with distilled water and HNO_3. The standards were prepared once and used for all AAS work with the exception of irons in which case the standards were made up immediately before instrumental calibration. Background correction for lead (283.3 nm) was checked by running the samples at the 280.3 nm wavelength as well. No background correction was necessary. Chromium was analyzed in the presence of 2000 ppm of aluminum, which acts as an oxygen scavenger in the reducing flame.

X-Ray Fluorescene - All x-ray fluorescence analyses were conducted at the Crocker Nuclear Laboratory at the University of California, Davis.

Table 3

OPERATING PARAMETERS FOR ATOMIC ABSORPTION ANALYSIS

Element	Wavelength (nm)	Oxidant (with acetylene)
Cd	228.3	air
Cr	357.9	air
Cu	327.4	air
Fe	248.3	air
Ni	352.5	air
Pb	283.3	air
Zn	213.9	air

SECTION 4

EXPERIMENTAL RESULTS

A series of eight experimental runs on a sludge and wastepaper gasification system was conducted to evaluate the gasifier performance with various fuels, to measure particulate and gaseous emissions, and to perform a metals balance. Gasifier run summaries, operating data, mass and energy balances, particulate and gaseous emissions, metals balance, metals analysis quality assurance, and particle and metal size distribution are presented in this section.

GASIFIER RUN SUMMARIES

To accomplish the experimental goals of the project, four different mixtures of sludge and wastepaper were gasified in a series of eight gasifier runs. The data collected during each gasifier run can be categorized into six areas: mass balance data, energy balance data, particle emission data (EPA Method 5), metals balance data, gaseous emission data, and particle size distribution data. In Table 4, the data collected during each run is presented.

OPERATING DATA

The gasifier operating data is presented below and is discussed in four parts.

Fuel Characteristics

To quantify physical and chemical characteristics, the gasifier fuels were tested for moisture content, energy content, bulk density, and ultimate analysis. A description of these test methods was presented in Section 3 and a summary of fuel results is found in Table 5.

There were four different mixtures of sludge and wastepaper tested, indicated by four batch numbers. The highest proportion of sludge is associated with the highest batch number. Thus batch #4 had a higher proportion of sludge than batch #3, and so on. The variation in the sludge content of the fuel is reflected in the residue fraction; due to the high ash content of the sludge. Also, fuel with a larger proportion of sludge has a higher bulk density. It is believed that the sludge acts as a binder during the densification process.

Table 4

SUMMARY OF DATA COLLECTED

Data Collected	Run Number							
	33	36	37	38	40	41	42	44
Mass Balance	X	X	X	X	X	X	X	X
Energy Balance		X	X	X	X	X	X	X
Particle Emissions	X	X	X	X	X	X	X	X
Gaseous Emissions		X	X	X				
Metals Balance	X	X	X	X	X	X	X	
Particle Size Distribution						X	X	X

Table 5

FUEL SUMMARY

Run No.	Batch No.	Moisture Content % by dry weight	Energy Content Dry Basis HHV, MJ/kg	Bulk Density (kg/m³)	Ultimate Analysis, % by weight					
					C	H	O	N	S	Residue
33	4	8.88	17.12[a]	595	44.36	5.72	40.57	0.63	0.22	8.5
36	2	8.61	18.71	343	47.54	5.74	41.69	0.36	0.17	4.5
37	3	12.41	18.52	395	45.17	5.66	42.81	0.37	0.19	5.8
38	4	9.68	17.12	546	44.31	5.60	39.70	0.60	0.29	9.5
40	1	9.85	19.02	337	45.51	5.80	44.21	0.33	0.05	4.1
41	2	8.39	18.66	364	44.77	5.69	43.30	0.39	0.15	5.7
42	3	10.2	17.99	334	44.47	5.70	42.34	0.44	0.15	6.9
44	2	6.5	19.43	334	46.32	5.75	44.67	0.12	0.04	3.1

[a] Same as Run 38

Because sludge/wastepaper fuel is essentially a biomass fuel, there is a significant fraction of oxygen in the fuel. Thus, sludge/wastepaper fuels like all biomass fuels have lower heating values than coal.

Char and Fly Ash Characteristics

A summary of the chemical properties of the char is presented in Table 6 and a summary of the chemical properties of fly ash (collected in the high efficiency cyclone shown in Figure 2) is presented in Table 7. A description of the analysis methods used to determine the char and fly ash properties is found in Section 3.

Producer Gas Analysis

Producer gas analysis data were taken for all gasifier runs except Run 33 with the producer gas analysis system described in Section 3. Average values of the dry producer gas composition, moisture content, and energy content are reported in Table 8. The average values of the dry producer gas composition were obtained by averaging gas values after the warm-up period (the first 90 minutes of the run is the warm-up period), excluding down time for refueling and repairs. A graphical profile of the variations in the producer gas composition throughout the gasifier run are presented in a series of computer generated plots found in Appendix D.

During Run 44, a sample of the producer gas was taken and analyzed using a gas chromotograph (GC). A gas bomb was purged with producer gas for a period of 20 minutes. The results of the GC analysis are presented in Table 8 under the column Run 44 GC The average values obtained from the gas analysis system described earlier during this twenty minute period are shown in parentheses next to the Run 44 GC values.

Measurements of CO for all gasifier runs are considered to be the most reliable. The CO analyzer operated well and the calibration was easily maintained throughout the run. There was excellent correlation in CO reading between the GC and the gas analysis system during Run 44.

The H_2 values were generally reliable although the H_2 analyzer was inoperative during Run 40. Hydrogen gas concentrations for Run 44 measured by the GC were lower than those measured by the gas analysis system. This deviation could have been due to diffusion of H_2 gas from the GC gas bomb between the time the sample was gathered and the time the sample was analyzed.

The range of CO_2 values measured by the gas analysis system varied between 13.16 and 14.29 percent. However the CO_2 analyzer was inoperative during Runs 40, 41, 42. There was a significant difference between the CO_2 concentrations measured by the gas analyzer and the GC. No explanation for this difference is offered.

Table 6

CHAR SUMMARY

Run No.	Batch No.	Energy Content Dry Basins HHV (MJ/kg)	Ultimate Analysis % by weight					
			C	H	O	N	S	Residue
33	4	16.67	58.37	0.29	0.00	0.36	0.36	50.7[a]
36	2	18.97	53.10	0.55	0.48	0.36	0.21	45.3
37	3	14.74	46.76	0.48	0.69	0.36	0.21	51.5
38	4	15.22	47.00	0.50	0.05	0.45	0.20	51.8
40	1	19.90	55.44	0.55	1.47	0.34	0.20	42.0
41	2	20.46	55.94	0.59	1.20	0.28	0.29	41.7
42	3	15.60	39.36	0.43	1.29	0.26	0.26	58.4
44	2	19.97	57.60	0.50	5.50	0.26	0.14	36.0

[a] As oxides, therefore total is greater than 100%.

Table 7

FLY ASH SUMMARY

Run No.	Batch No.	Energy content Dry Basis, HHV, (MJ/kg)	Ultimate Analysis % by weight					
			C	H	O	N	S	Residue
33	4	19.27	56.88	0.69	0.16	0.62	0.65	41.0
36	2	21.02	61.58	0.55	0.65	0.47	0.35	36.4
37	3	19.99	57.94	0.82	1.03	0.61	0.30	39.3
38	4	18.42	52.65	0.73	1.21	0.70	0.71	44.0
40	1	21.99	61.87	0.73	1.39	0.49	0.62	34.9
41	2	20.85	60.63	0.71	0.99	0.46	0.51	36.7
42	3	20.31	57.20	0.63	0.74	0.47	0.66	40.3
44	2	20.73	57.75	0.67	0.48	0.30	0.40	40.4

Table 8

COMPOSITION AND ENERGY CONTENT OF PRODUCER GAS

Item	Run 36	Run 37	Run 38	Run 40	Run 41	Run 42	Run 44	Run 44 GC[d]
Dry Gas Composition (By volume), %								
CO, %	20.56	19.89	17.93	20.89	19.68	19.83	20.04	19.88 (19.94)
H_2, %	15.44	15.36	14.52	15.50[c]	15.85	16.14	16.59	15.79 (16.44)
CH_4[a], %	5.38	3.68	2.21	4.26	3.49	2.79	3.09	2.69 (3.47)
C_2H_4[a], %	2.31	1.58	0.95	1.83	1.50	1.19	1.33	0.82 (1.48)
CO_2, %	13.83	13.78	13.16	13.50[c]	13.50[c]	13.50	14.29	10.79 (14.20)
N_2[b], %	42.48	45.71	51.23	44.02	45.98	46.55	44.66	50.03[e] (44.48)
Gas moisture content (by wet volume), %	15.47	16.10	16.22	14.31[c]	14.12	14.42	13.69	13.69 (NA)
Gas Energy Content, MJ/m^3 (Dry gas, LHV, 25°C, 1 atm)	7.04	5.99	4.83	6.45	5.90	5.55	5.73	5.28 (5.98)

[a] Measured as total hydrocarbons, CH_4 assumed to be 70% of THC, C_2H_4 assumed to be 30% of THC

[b] N_2 includes nitrogen, argon, and trace amounts of nitrogen oxides. N_2 is determined by difference, N_2, = 100% - ($CO + H_2 + THC + CO_2 + O_2$)

[c] Assumed typical value, experimental data not available

[d] Using gas chromatograph values, gas analysis averages during this 20 minute period shown in parentheses.

[e] Includes 0.84% O_2

The THC gas analysis measurements are considered to be the least reliable. Despite calibration before, during, and after the gasifier runs, the THC analyzer was extremely sensitive to producer gas analysis flow variations. These variations were due to tar and particulate matter collecting in the gas analysis sample train (see Figure 5). Thus, constant monitoring of the flow into the THC analyzer was required. Despite constant monitoring of the flow into the THC analyzer, the values presented in Table 8 could vary ± 10%. There was a large difference between the THC values measured by the gas analyzer and those measured by the GC. No explanation for this difference is offered.

Nitrogen concentrations were calculated by difference. Thus the variation in the N_2 concentration is the sum of the variation in each of the other four components.

The dry gas energy content is calculated using the average producer gas composition values. Because the energy content of THC is much greater than the energy contents of CO and H_2, the THC fraction of the producer gas greatly influences the overall energy content of the producer gas. Because of the inaccuracy in measuring the THC fraction of the gas, a variation of ± 5% can be expected in the gas energy content values reported in Table 8.

Operational Summary

An operational summary for each gasifier run conducted for this project is presented in Table 9. The fuel, char, fly ash, slag, and air input rates were measured directly using methods described in Section 3. The gas output rate is calculated by performing a nitrogen balance on the gasifier (see Appendix A). The reduction zone and lower reduction zone temperatures were measured using thermocouples in locations shown in Figure 3. The gas outlet temperature was measured at the cyclone.

Temperature, pressure, and producer gas composition data were sampled automatically throughout the gasifier runs. Plots showing the variation of temperature, pressure, and gas composition are presented in Appendix D.

MASS AND ENERGY BALANCES

Mass and energy balances for all gasifier runs except Run 33 were calculated using the computer program described in Appendix A. Listings for the program and printouts for each run are found in Appendix B. A summary of mass and energy balances for these runs is presented in Table 10. Run 44GC is identical with Run 44 except that the producer gas constituents are based on gas chromatograph measurements rather than gas analysis measurements (see Table 8).

The percent closure can be used as an indication of the accuracy of the mass balance. A perfect mass balance should have zero percent closure. A negative percent closure indicates that more mass is leaving the gasifier

Table 9

OPERATIONAL SUMMARY

Item	RUN 33	RUN 36	RUN 37	RUN 38	RUN 40	RUN 41	RUN 42	RUN 44
Fuel batch no.	#4	#2	#3	#4	#1	#2	#3	#2
Fuel rate, Kg/hr	92.2	105.3	96.6	100.7	100.9	107.1	99.7	102.7
Char production rate, kg/hr	12.6	13.5	13.8	14.3	13.9	14.8	14.8	14.4
Fly ash collection rate, kg/hr	0.24	0.47	0.68	0.80	0.73	0.66	0.71	0.28
Slag rate, Kg/hr	0.81	0.19	0.11	0.36	0.07	0.07	0.13	0.08
Air input rate, m^3/min (20^oC, 1 atm)	1.93	1.94	1.96	1.95	2.01	1.96	1.96	1.92
Gas ouput rate, m^3/min (20^oC, 1 atm)	NA	3.60	3.39	3.00	3.60	3.37	3.33	3.40
Average reduction zone temperature, ^oC	993	944	963	997	953	974	962	982
Average lower reduction zone temperature, ^oC	NA	779	794	828	784	804	793	815
Average gas outlet temperature, ^oC	549	582	591	610	582	610	590	602
Net run time, min	184	220	277	93	209	278	265	179

NA = Not available

Table 10

MASS AND ENERGY BALANCES FOR GASIFIER RUNS

Run number	36	37	38	40	41	42	44	44 GC
Fuel batch no.	#2	#3	#4	#1	#2	#3	#2	#2
Mass Balance								
Air rate, kg/hr	140.03	141.62	140.75	144.87	141.54	141.90	138.72	138.72
Dry fuel rate, kg/hr	96.24	84.62	90.93	90.91	98.10	89.53	96.02	96.02
Fuel moisture, kg/hr	9.06	11.98	9.77	9.99	9.00	10.17	6.68	6.68
Dry gas rate, kg/hr	230.48	218.49	196.03	230.71	215.85	213.82	217.33	195.56
Gas moisture rate, kg/hr	33.47	32.82	29.32	30.84	28.45	28.79	22.72	20.62
Char rate, kg/hr	13.50	13.80	14.30	13.90	14.80	14.80	14.40	14.40
Fly ash rate, kg/hr	0.47	0.68	0.80	0.73	0.66	0.71	0.28	0.28
% Closure	-13.28	-11.58	0.41	-12.38	-4.47	-6.84	-5.51	4.37
Energy Balance								
Energy in char, percent	14.22	12.98	13.98	16.00	16.53	14.34	15.41	15.41
Energy in fly ash, percent	0.55	0.87	0.95	0.90	0.75	0.90	0.31	0.31
Sensible energy in gas, percent	13.99	15.36	13.98	14.01	12.80	14.00	11.65	10.39
Chemical energy in gas, percent	91.36	83.78	60.39	86.85	70.27	74.34	67.64	56.49
Energy losses, percent	-20.11	-12.99	10.70	-17.71	-0.34	-3.57	4.98	17.39
Hot gas efficiency, percent	98.57	93.00	69.95	94.54	77.85	82.86	74.21	62.74
Cold gas efficiency, percent	84.58	77.63	55.97	80.52	65.05	68.86	62.56	52.35

than is entering the gasifier, while a positive sign indicates that mass is accumulating in the gasifier. The accuracy of the energy balance is obviously affected by the mass balance. The accuracy of the energy balance can be determined by noting the percent energy losses. Based on the gasifier design the percent energy losses should be between 2 and 5 percent. Based on the percent closure and the percent energy losses, it can be concluded that the mass and energy balance results for Runs 36, 37, 40 are suspect due to errors in mass balance measurements or producer gas analysis. It is important to compare the mass and energy balance results from Runs 44 and 44GC. Note that only a small variation in the combustible constituents concentration (CO: 20.04 to 19.88, H_2: 16.59 to 15.79, CH_4: 3.09 to 2.69, and C_2H_4: 1.33 to 0.82 percent) created a large variation in the cold gas efficiency (62.56 to 52.35 percent). This example illustrates the sensitivity of gasifier energy balance data to variations in the producer gas composition.

PARTICLE AND GASEOUS EMISSIONS

Particle emission results based on the EPA Method 5 sampling protocol were conducted for Runs 36, 37, 38, 40, 41, 42 by the California Air Resources Board. A particle emission evaluation of the stack gases of Run 33 was conducted, but is not presented here due to insufficient data. The results of the Method 5 analyses is presented in Table 11.

Gaseous emissions were measured during Runs 36, 37, and 38 using the California Air Resources gas monitoring van. The results of these tests and the results of Fyrite tests during Runs 40, 41, and 42, are presented in Table 12.

METAL MASS BALANCE

Metal mass balances were performed for all gasifier runs except Run 44. Samples of fuel, char, fly ash, slag, and particulate emissions were analyzed for seven metals; cadmium, lead, zinc, nickel, and copper, chromium, and iron. Because batch #2 was used during Runs 36 and 41, batch #3 was used during Runs 37 and 42, and batch #4 was used during Runs 33 and 38, fuel samples from these runs were lumped together and analyzed. The gasifier runs dealing with metal balances are arranged from lowest sludge concentration to highest. That is, data for Run 40, is presented first, followed by Runs 36 and 41, Runs 37 and 42, and Runs 33 and 38.

Concentrations of seven metals in the fuel samples are presented in Table 13. The results from the metals mass balances are presented in Figures 8 through 13, in Table 14, and in Appendix E.

The percentage metal found in each gasifier system stream is plotted against the normalized fuel concentrations for the four different fuels. The fuel concentrations were normalized with respect to the fuel concentrations of Run 40, which had the least amount of sludge and metals.

Table 11

PARTICLE EMISSION RESULTS[a]

Measurement	Gasifier Run Number					
	36	37	38	40	41	42
Isokinetic ratio, %	97.4	96.5	94.3	92.5	93.6	88.6
Corrected sample volume, DSCM	1.345	1.402	1.310	1.239	1.161	1.129
Particle concentration,[b] mg/DSCM	64.32 (192.96)	59.54 (178.62)	54.59 (163.77)	11.90 (35.70)	26.15 (78.45)	13.18 (39.54)
Particle emissions, kg/hr	0.1080	0.1051	0.0922	0.0195	0.0397	0.0206
Stack flow, SCM/min	28.00	29.42	28.15	27.36	25.35	26.03
Stack velocity, m/sec	7.01	7.25	6.83	6.77	6.25	6.19
Percent H_2O in stack	5.0	5.0	4.7	4.5	4.8	5.5
Percent O_2 in stack	17.00	17.00	17.00	17.00	17.00	17.00
Percent CO_2 in stack	4.00	4.00	4.00	4.00	4.00	4.00
Percent CO in stack	0.00	0.00	0.00	0.00	0.00	0.00
Particle mass catch on filter, mg	86.5	83.5	71.5	14.7	30.4	14.9
Stack temperature, °C	417	396	390	416	410	382
Sampling time, min	64	64	64	64	64	64

[a] Based on EPA Method 5

[b] Values in parenthesis are corrected for 12% CO_2

DSCM = dry standard cubic meter, 20°C, 1 atm pressure

Table 12

GASEOUS EMISSION RESULTS

	Gasifier Run Number					
Gas	36	37	38	40	41	42
O_2, %	16.0	17.3	16.9	17.5[a]	17.5[a]	17.0[a]
CO_2, %	4.33	3.19	3.95	4.5[a]	5.0[a]	4.0[a]
CO, ppmv	16.5	16.8	15.1	NA	NA	NA
THC, ppmv	12.7	4.20	1.39	NA	NA	NA
NO_x, ppmv	98.6	99.2	121	NA	NA	NA
SO_x, ppmv	55.5	62.6	105	NA	NA	NA

[a] Determined using Fyrite gas absorption analyzers.

ppmv = parts per million, volume basis.

Table 13

CONCENTRATIONS OF METAL IN FUEL

	Concentrations of metal, ppm[a]			
	Gasifier Run Number			
Metal	40	36,41	37,42	33,38
Cadmium	2.05	2.40	3.20	4.85
Lead	37.2	38.3	49.4	80.3
Zinc	207.	209.	278.	364.
Nickel	21.6	28.2	33.7	80.7
Copper	109.	121.	147.	200.
Chromium	108.	136.	168.	255.
Iron	2500.	2870.	3690.	5160.

[a] Concentrations presented as ppm of dry fuel.

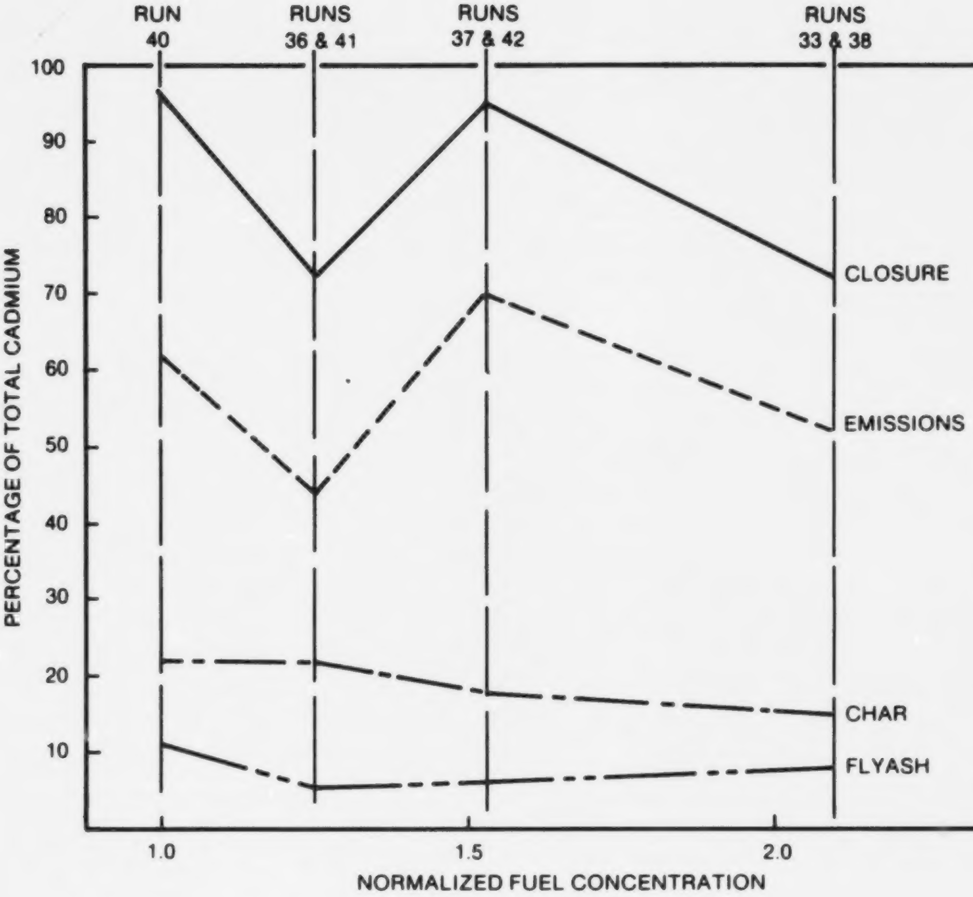

Figure 8. Average percentage of cadmium recovered in the gasification system output streams at various fuel concentrations. Fuel concentrations are normalized with respect to Run 40 fuel.

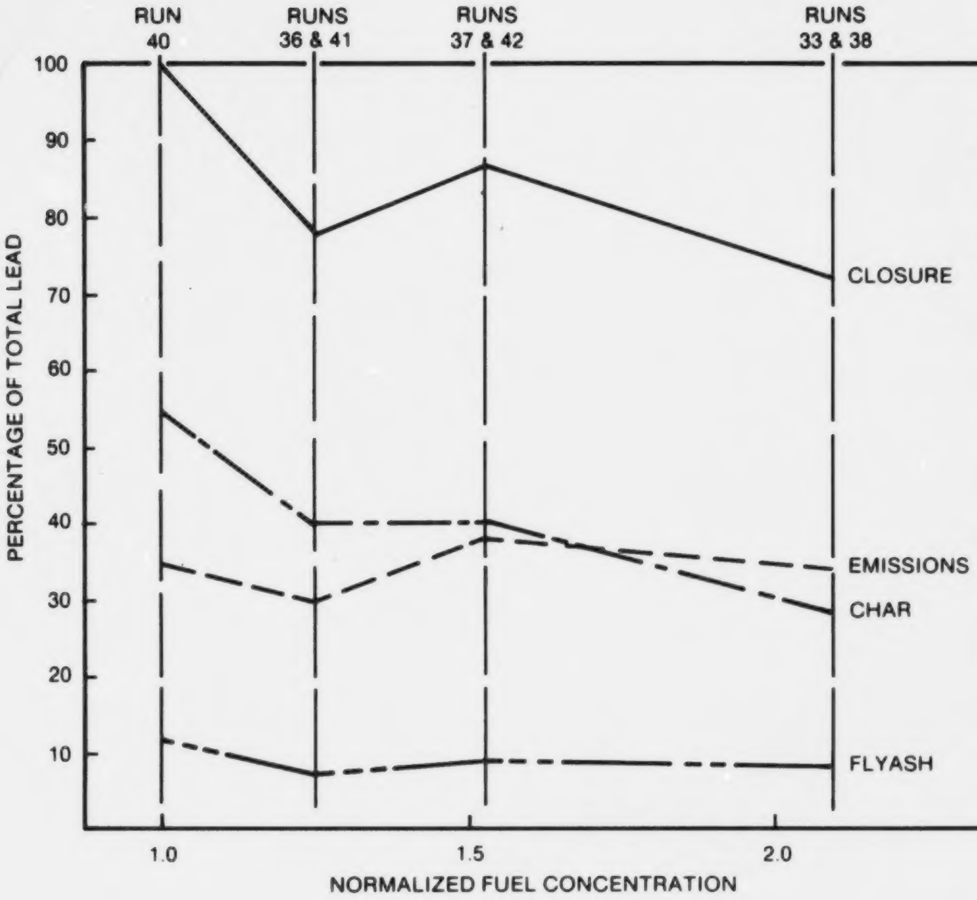

Figure 9. Average percentage of lead recovered in the gasification system output streams at various fuel concentrations. Fuel concentrations are normalized with respect to Run 40 fuel.

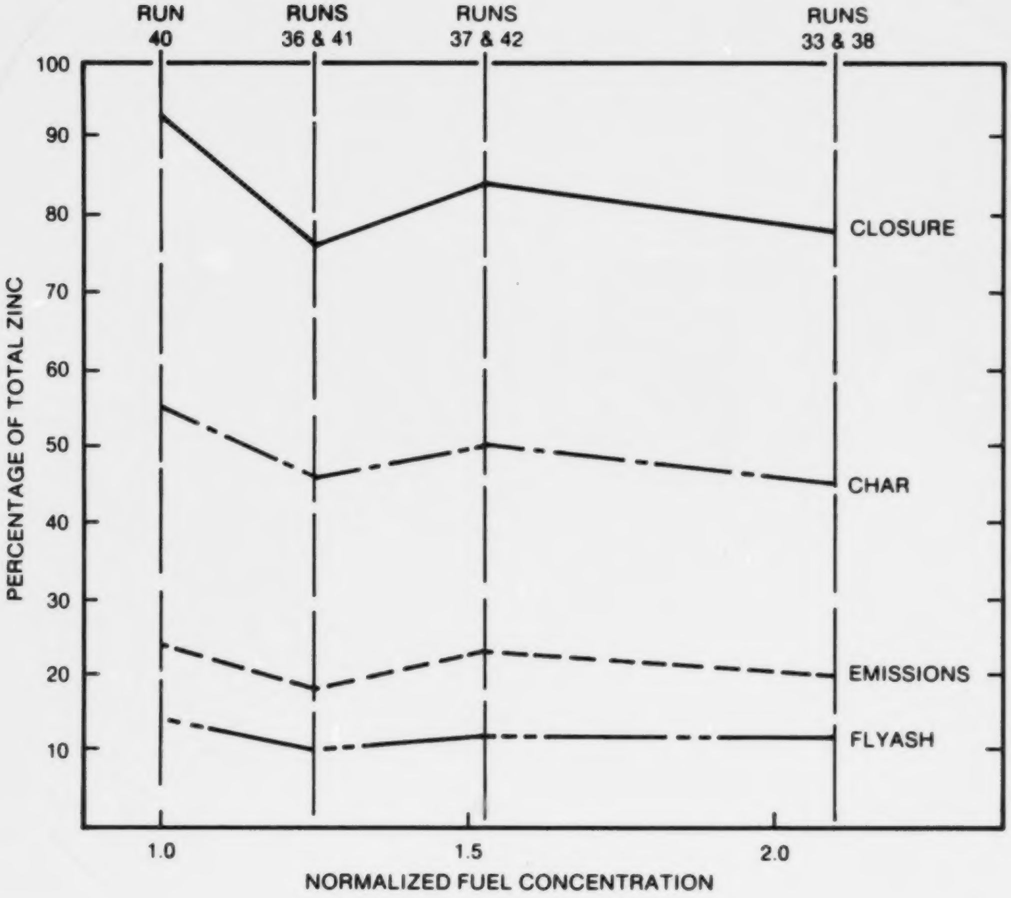

Figure 10. Average percentage of zinc recovered in the gasification system output streams at various fuel concentrations. Fuel concentrations are normalized with respect to Run 40 fuel.

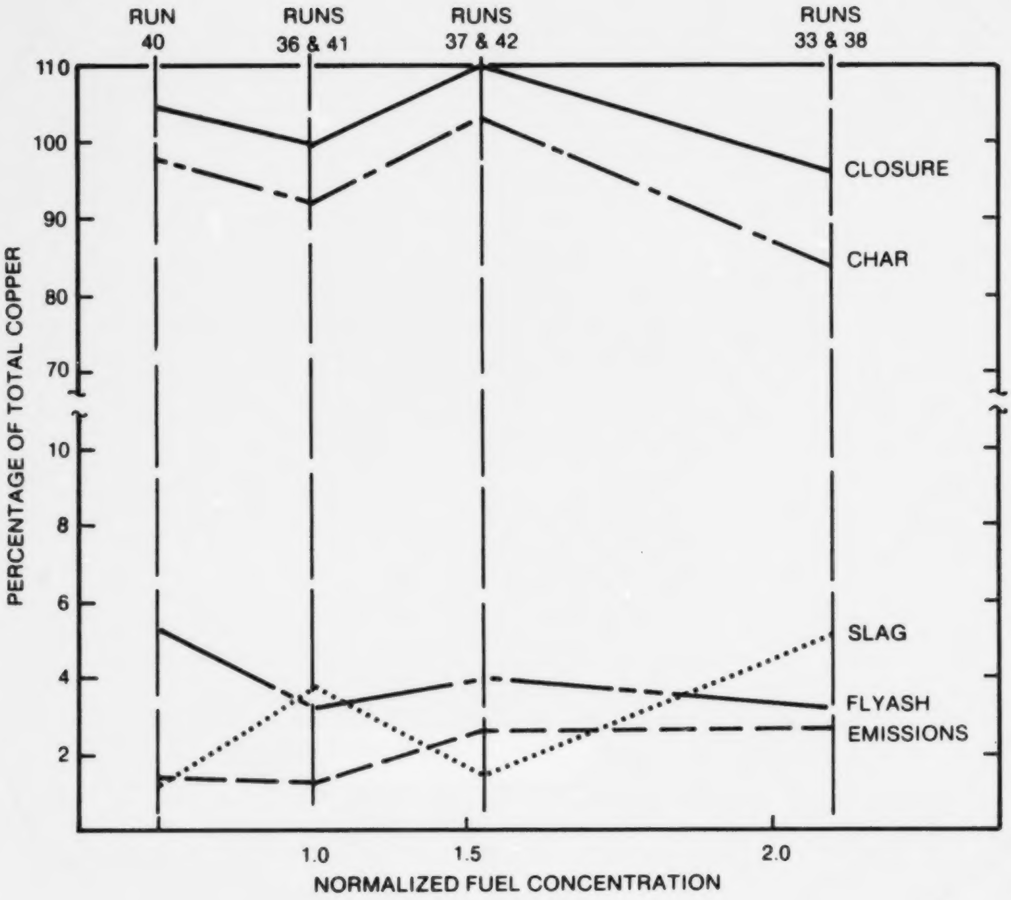

Figure 11. Average percentage of copper recovered in the gasification system output streams at various fuel concentrations. Fuel concentrations are normalized with respect to Run 40 fuel.

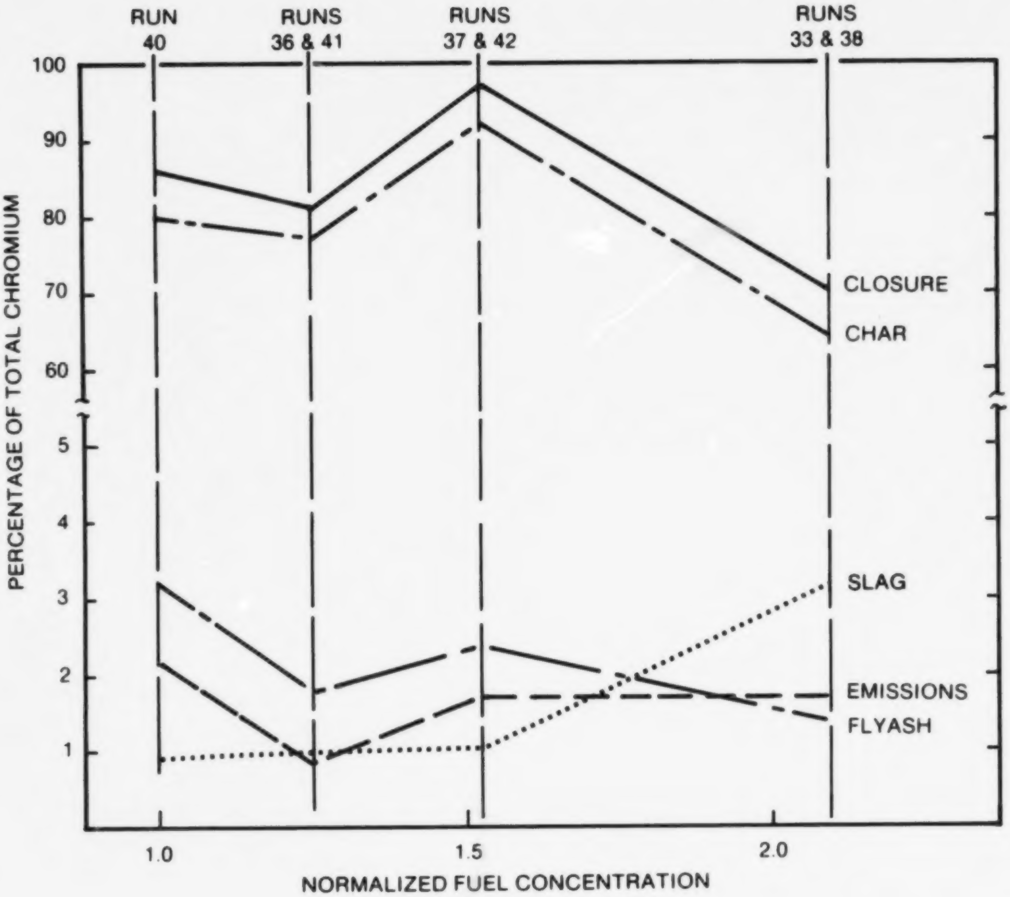

Figure 12. Average percentage of chromium recovered in the gasification system output streams at various fuel concentrations. Fuel concentrations are normalized with respect to Run 40 fuel.

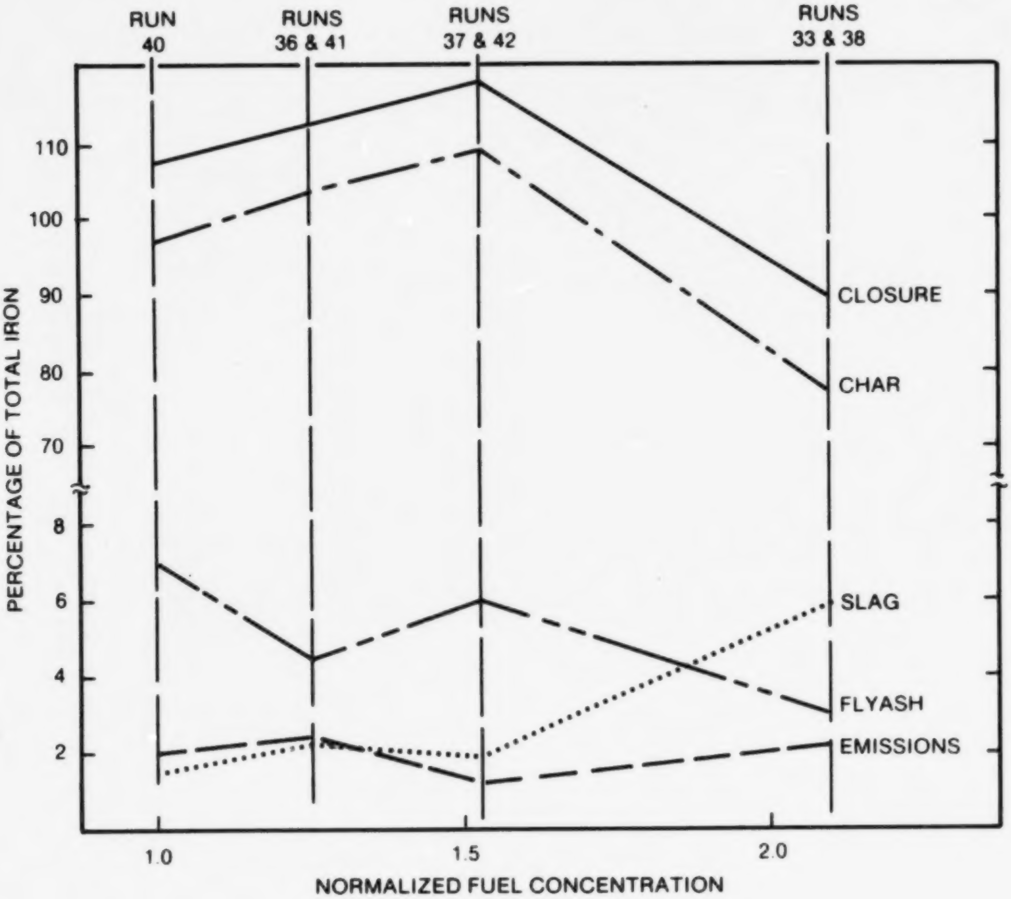

Figure 13. Average percentage of iron recovered in the gasification system output streams at various fuel concentrations. Fuel concentrations are normalized with respect to Run 40 fuel.

Table 14

NICKEL MASS BALANCE RESULTS

Stream	Concentrations and percentages of nickel for each gasifier run						
	40	36	41	37	42	33	38
Fuel, ppm	21.6	28.2		33.7		80.7	
Char, ppm	182.	119.	233.	203.	331.	290.	227.
% total	129.0	59.2	124.7	98.2	162.4	54.4	44.3
Fly ash, ppm	184.	105.	271.	153.	357.	334.	188.
% total	6.8	1.8	6.5	3.7	8.4	1.2	2.0
Slag, ppm	453.	366.	669.	361.	671.	384.	363.
% total	1.6	2.6	1.7	1.4	2.9	4.6	1.8
Emissions, $\mu g/m^3$	124.	54.3	136.	2310	355.	1180	24.7
% total	10.4	3.4	7.5	143.0	18.4	33.9	0.6
Total nickel recovered, %	147.8	67.0	140.4	246.3	192.1	94.1	48.7

The metals mass balance results are presented in two sections; volatile metals and non-volatile metals.

Volatile Metals - Three metals that exhibited volatile behavior during the gasification process are cadmium, lead, and zinc. Other metals have been classified as volatile by previous work on sludge incinerators (3,23,25,36), especially mercury and selenium, but these elements were not present in the gasifier fuel in sufficient quantity to perform an accurate mass balance. Of the volatile metals studied, cadmium was the most volatile (Figure 8), followed by lead (Figure 9), and zinc (Figure 10).

The char contained substantial quantities of all three volatile metals; 38 to 55 percent of the zinc, 25 to 55 percent of the lead, and 16 to 25 percent of the total cadmium. The fly ash contained approximately 10 percent of the total metal for all three of the volatile metals. Although the fly ash accounted for a small amount of the total metal, fly ash had higher volatile metal concentrations than the char, but a lower mass than the char (Table 9). The slag accounted for less than 1 percent of the total mass of each of the volatile metals and is not shown in Figures 8, 9, and 10.

There appears to be little change in the behavior of the volatile metals with changes in the fuel concentrations. Based on the shape of the closure line shown in Figures 8, 9, and 10, it can be concluded that the deviations from closure are largely due to fuel concentrations being inaccurate. The most difficult of the gasifier streams to accurately characterize was the fuel, due to the large amounts gasified during each run and its non-homogenous nature.

Non-Volatile Metals - Four metals exhibited behavior characteristic of non-volatile matrix elements, Cu, Cr, Fe and Ni. The term matrix element refers to elements which are components of the ash matrix, as opposed to the volatile elements which volatize at high temperatures and condense back on the particle surface at lower temperatures. The results of the mass balances for copper, chromium, and iron are presented in Figures 11, 12, and 13, respectively. The results for nickel are presented in Table 14.

From Figures 11, 12, and 13 it can be seen that nearly all the copper, chromium and iron can be accounted for by the char. It is important to note that the fly ash contained more copper, chromium and iron than the emissions for all the fuels tested. Only 2 to 4 percent of the total copper, chromium or iron was present in the emissions, indicative of their stable behavior during the gasification process. The slag accounted for small amounts of copper, chromium, and iron (usually greater than 1 percent), and varied with the amount of sludge present in the fuel. Large amounts of sludge yielded larger quantities of slag, which accounted for larger quantities of matrix elements.

The closure lines for copper, chromium and iron are very similar to one another. This suggests that the variance from closure could be due to fuel sampling and analysis.

The results of the nickel mass balance were not plotted due to a large variance in the closures, even for duplicate runs. The nickel mass balance results are presented in tabular form in Table 14. Initially, there was concern over the possible formation of nickel tetracarbonyl, which would cause nickel metal to be volatized and found either in the fly ash or emission particles. To verify the occurrance of nickel tetracarbonyl, Draeger detection tubes were used to test for the presence of nickel tetracarbonyl in the fuel hopper and at the cyclone. Tests for nickel tetracarbonyl proved negative at both locations.

METALS ANALYSIS QUALITY ASSURANCE

To determine the accuracy of the metals analysis used in this study, two samples of NBS coal fly ash were prepared using the same dissolution procedures used for the gasifier char and fly ash samples. Then the NBS coal sample (Table 15) was analyzed for seven metals using AAS. A comparison of these results and the NBS certified values is presented in Table 16. The concentration of cadmium in the NBS sample was below the detection limit of the AAS using an air-acetylene flame. Thus, the concentration of cadmium was not determined. There was good agreement between the values determined by AAS and the NBS certified values for Cr, Cu, Fe, Ni, Pb, and Zn.

PARTICLE AND METAL SIZE DISTRIBUTION

Particle and metal size distribution studies were conducted by the California Air Resources Board (CARB) during Runs 40, 41, and 42. A Pilot Mark 3 impactor and an Anderson Mark 3 impactor were used to gather size distribution data on the emissions from the gasifier system. Three impactor runs were conducted during Run 40, Run 41, and Run 42.

The procedure to obtain the particulate matter distribution data and the methods used to measure the metal mass at each impactor stage were presented in Section 3. The metal size distributions are based on the fraction of the total metal mass collected in the impactor at each stage. The metal mass at each impactor stage is found by subtracting the metal mass on a blank impactor substrate from the metal mass on the particle laden impactor substrate. Because the metal size distributions are dependent only on the metal mass found on each impactor stage and the gas flowrate through the impactor (which fixes the cut diameter), metal size distributions can be determined for impactor runs for which the particle (mass) size distributions are not available.

The impactor data used to generate particle and metal size distributions is presented in Table 17. Based on the information presented in Table 17, less than half of data gathered could be used to generate par ticle and metal size distributions without modification. During impactor runs PT1 and AN1, and AN2 particle size distribution data could not be used due to erroneous mass readings. Metal distribution data could not be used for impactor runs AN1, AN3 and PT3 because one substrate sample for each run was lost during

Table 15

ANALYSIS OF NBS - 1632A COAL SAMPLE

Element	Concentration, ppm	Element	Concentration, ppm
aluminum	31,000*	magnesium	1000*
antimony	0.6*	manganese	28 ± 2
arsenic	9.3 ± 1.0	mercury	0.13 ± 0.03
cadmium	0.17 ± 0.02	nickel	19.4 ± 1.0
calcium	2300 ± 300	potassium	4200 ± 200
cerium	30*	rubidium	31*
cesium	2.4*	scandium	6.3*
chromium	34.4 ± 1.5	selenium	2.6 ± 0.7
cobalt	6.8*	sodium	840 ± 40
copper	16.5 ± 1.0	sulfur	16,200 ± 300
europium	0.5*	thorium	4.5 ± 0.1
gallium	8.5*	titanium	1800*
hafnium	1.6*	aranium	1.28 ± 0.02
iron	11,000 ± 200	vanadium	44 ± 3
lead	12.4 ± 0.6	zinc	28 ± 2

* Not a certified value, based on non-reference method

Note: a) percent ash in sample = 22% dry basis

b) two analytical methods were used on all elements for calcium (3 methods used) and iron (4 methods used)

Table 16

DETERMINATION OF METALS ANALYSIS ACCURACY USING AN NBS CERTIFIED COAL SAMPLE

Element	Metal Concentration, ppm	
	This study (AAS)	NBS certified (1632a)
Cd	NA	0.17 ± 0.02
Cr	34.1	34.4 ± 1.5
Cu	18.0	16.5 ± 1.0
Fe*	1.07%	1.11 ± 0.02%
Ni	20.1	19.4 ± 1.0
Pb	12.5	12.4 ± 0.6
Zn	30.1	28 ± 2

* Concentrations expressed in percent.

NA - Below detection limits of this study.

Table 17

IMPACTOR DATA USED TO GENERATE PARTICLE/METAL SIZE DISTRIBUTIONS

Gasifier Run Number	Impactor Run Number	Distribution Element							
		Particulate Matter	Cd	Pb	Zn	Ni	Cu	Cr	Fe
40	PT1	NM	UC	UC	X	UC	X	UC	X
	AN1	NM	BO	BO	BO	BO	BO	BO	BO
	AN2	NM	X	X	X	X	X	X	X
41	PT2	X	UC	X	X	UC	UC	X	X
	AN3	X	BO	BO	BO	BO	BO	BO	BO
	AN4	X	X	UC	X	UC	UC	X	UC
42	PT3	X	BO	BO	BO	BO	BO	BO	BO
	AN5	X	X	X	X	UC	X	UC	X
	AN6	X	X	X	X	UC	X	UC	X

PT = Pilat Mark 3 Impactor

AN = Anderson Impactor

X = Size distribution presented

UC = Size distribution based on total mass (not corrected for blank mass) presented

NM = Size distribution not available due erroneous mass reading

BO = size distribution not available due to boil over of sample during the digestion process the acid digestion due to boil over. The remainder of metals distribution data, indicated by UC in Table 17, was modified and used to generate metal-distributions. Modifications of this data were necessary because the total metal mass found on the particle laden substrate was less than the metal mass found on the blank substrate. Therefore the metal size distributions indicated by UC in Table 17 are based on total metal mass and not net metal mass. Based on comparisons of metal size distributions generated by net metal mass and by total metal mass, it was determined that for most metals, this modification was valid because it had little effect on the mass median aerodynamic diameter.

A comparison of the mass median aerodynamic diameters (MMAD) from size distributions generated by net metal mass and by total metal mass is presented in Table 18. Based on the results presented in Table 18, the MMAD generated by size distributions based on total metal mass (MMAD-total) were in most cases similar to the MMAD generated by size distributions based on net metal mass (MMAD-net). Actually, the MMAD-total should be larger than the MMAD-net. The difference between MMAD-total and MMAD-net varies directly with the metal concentration of the impactor substrate. Thus, if the metal concentration of the impactor substrate is large, then MMAD-total is much greater than MMAD-net. If the metal concentration of the impactor substrate is small, then the MMAD-total is only slightly greater than MMAD-net. Thus the validity of using the MMAD-total to predict the MMAD-net is a function of the metal concentration of the substrate.

Because the blank impactor substrate concentrations (Table 19) for Cr and Fe are relatively large the MMAD-total for Cr and Fe does not predict the MMAD-net well. The MMAD-total and MMAD-net are similar for Cd, Pb, Zn, Ni, and Cu because the blank impactor substrate concentrations for these metals is small.

Particle/metal size distribution graphs for all impactor studies are presented in Figures 14 to 21.

Table 18

MASS MEDIAN AERODYNAMIC DIAMETER

Gasifier Run Numbers	Impactor Run Number	Particulate Matter	Distribution Element (Diameter in microns)						
			Cd	Pb	Zn	Ni	Cu	Cr	Fe
40	PT1	NA	< 0.33[a]	< 0.33[a]	0.95 0.95[a]	2.5[a]	0.90 2.6[a]	2.8[a]	1.6 2.2[a]
	AN1	NA	NA	NA	NA	NA	NA	NA	NA
	AN2	NA	< 0.32 < 0.33[a]	< 0.32 < 0.32[a]	< 0.32 < 0.32[a]	4.5 4.5[a]	< 0.32 0.43[a]	4.6 4.6[a]	0.66 1.8[a]
41	PT2	0.95	< 0.33 < 0.33[a]	< 0.33 0.62[a]	< 0.33 < 0.33[a]	3.9[a]	< 0.33 0.48[a]	9.0[a]	6.0 6.0[a]
	AN3	0.31	NA	NA	NA	NA	NA	NA	NA
	AN4	0.31	< 0.31[a] < 0.31[a]	< 0.31[a]	< 0.31 < 0.31[a]	4.6[a]	< 0.31 < 0.31[a]	3.6 3.6[a]	1.3[a]
42	PT3	0.92	NA	NA	NA	NA	NA	NA	NA
	AN5	< 0.32	< 0.32 < 0.32[a]	< 0.32 < 0.32[a]	< 0.32 < 0.32[a]	5.5[a]	< 0.32 < 0.32[a]	5.0 5.0[a]	1 2[a]
	AN6	< 0.33	< 0.32 < 0.32[a]	< 0.32 0.38[a]	0.8 0.8[a]	6.5[a]	< 0.33[a]	4.0 4.5[a]	0.85 2.0[a]

[a] Mass medium aerodynamic diameter determined using size distributions generated by total metal mass, uncorrected for mass of blank; MMAD'S without subscript a used net metal mass.

NA - Not available.

Table 19

METAL CONCENTRATIONS OF BLANK IMPACTOR SUBSTRATES

Substrate	Concentration (ppm)						
Type	Cd	Pb	Zn	Ni	Cu	Cr	Fe
Pilat donut	10	140	23	93	9.2	300	270
Pilat disc	13	82	22	91	6.3	320	260
Pilat filter	13	190	41	83	14	430	590
Anderson substrate	1.6	79	24	81	8.2	250	260
Anderson filter	4.4	55	15	44	5.1	150	160

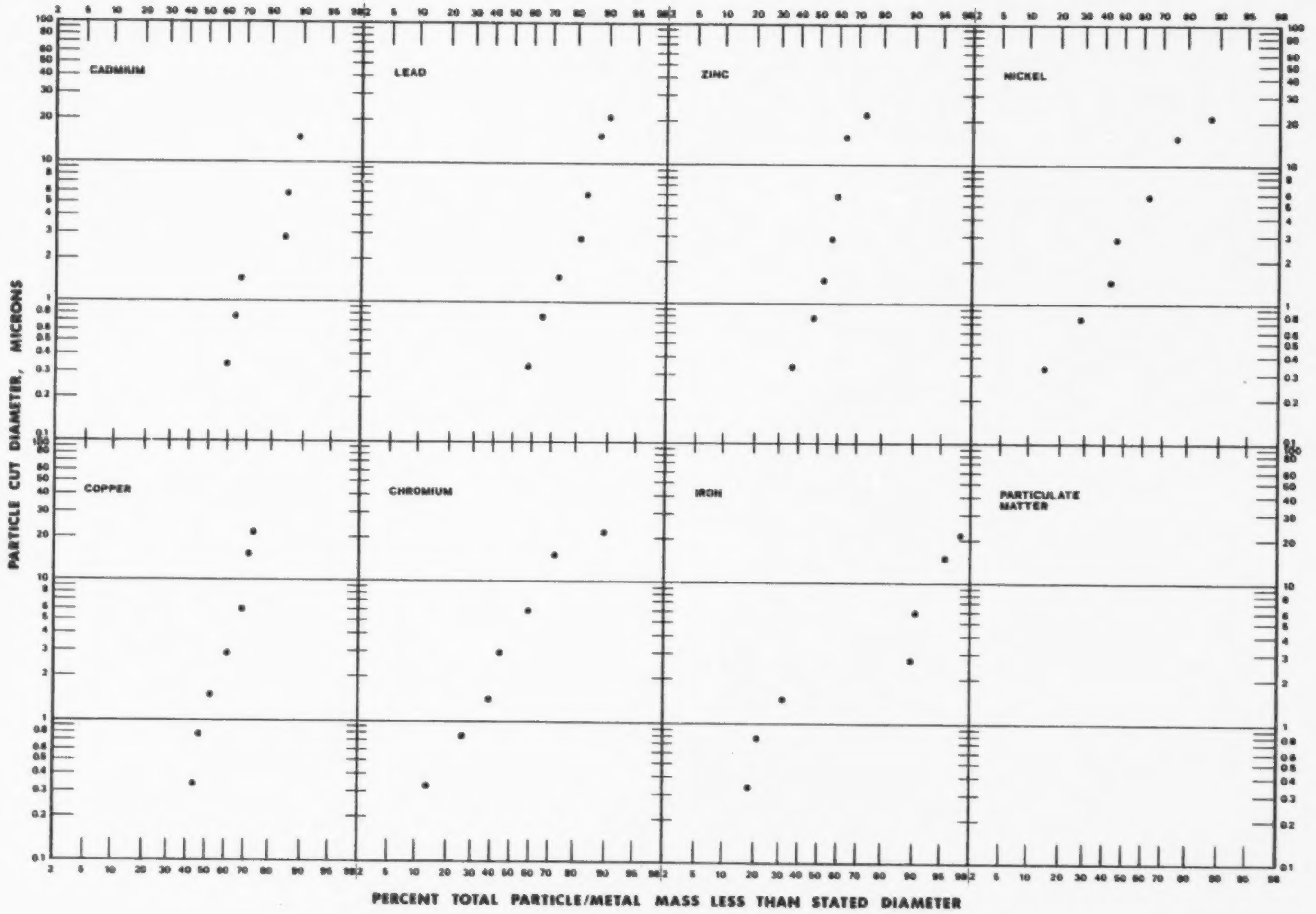

Figure 14. Metal size distributions, Run 40, PT-1.

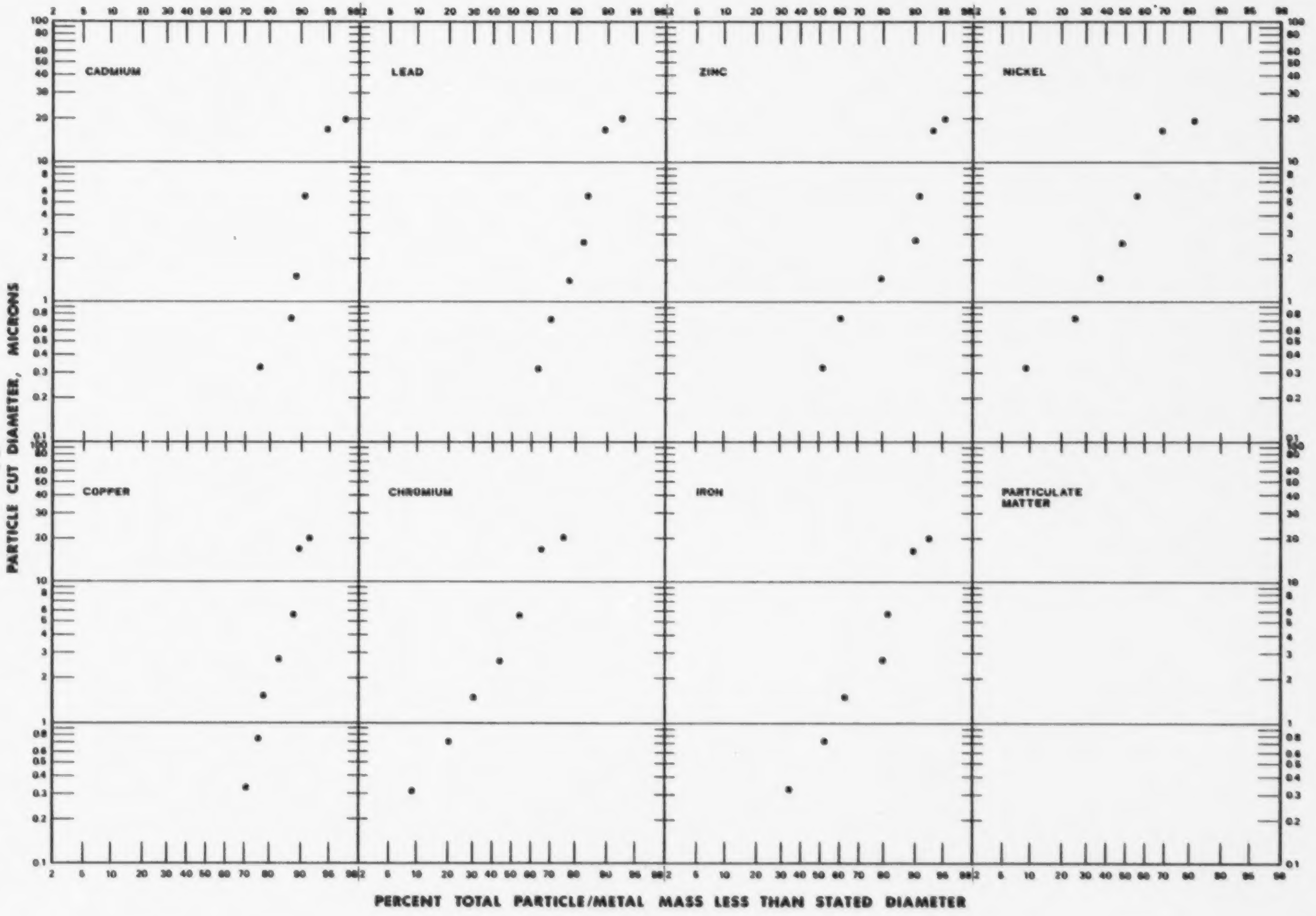

Figure 15. Metal size distributions, Run 40, AN-2.

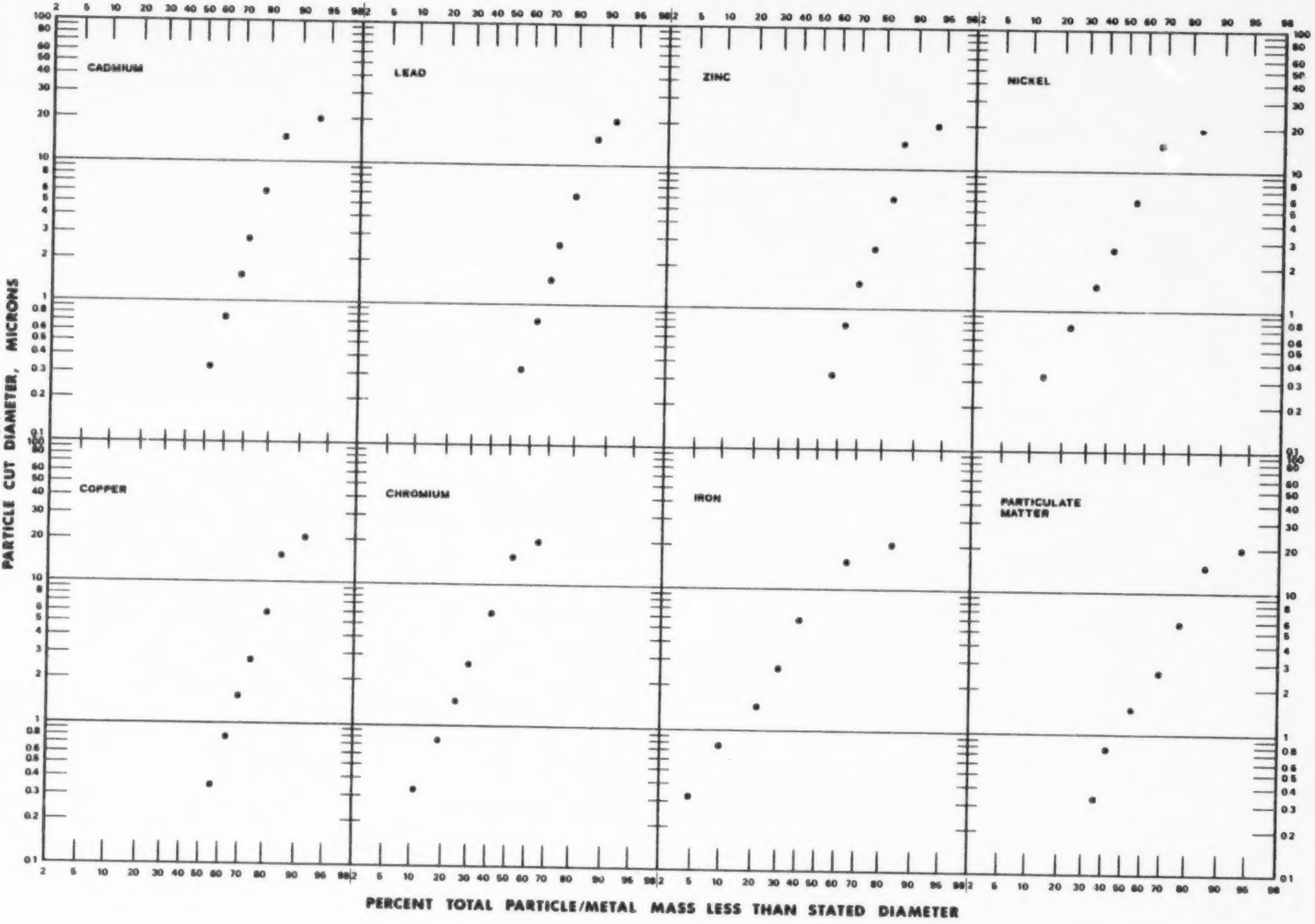

Figure 16, Particle/metal size distrubution, Run 41, PT-2.

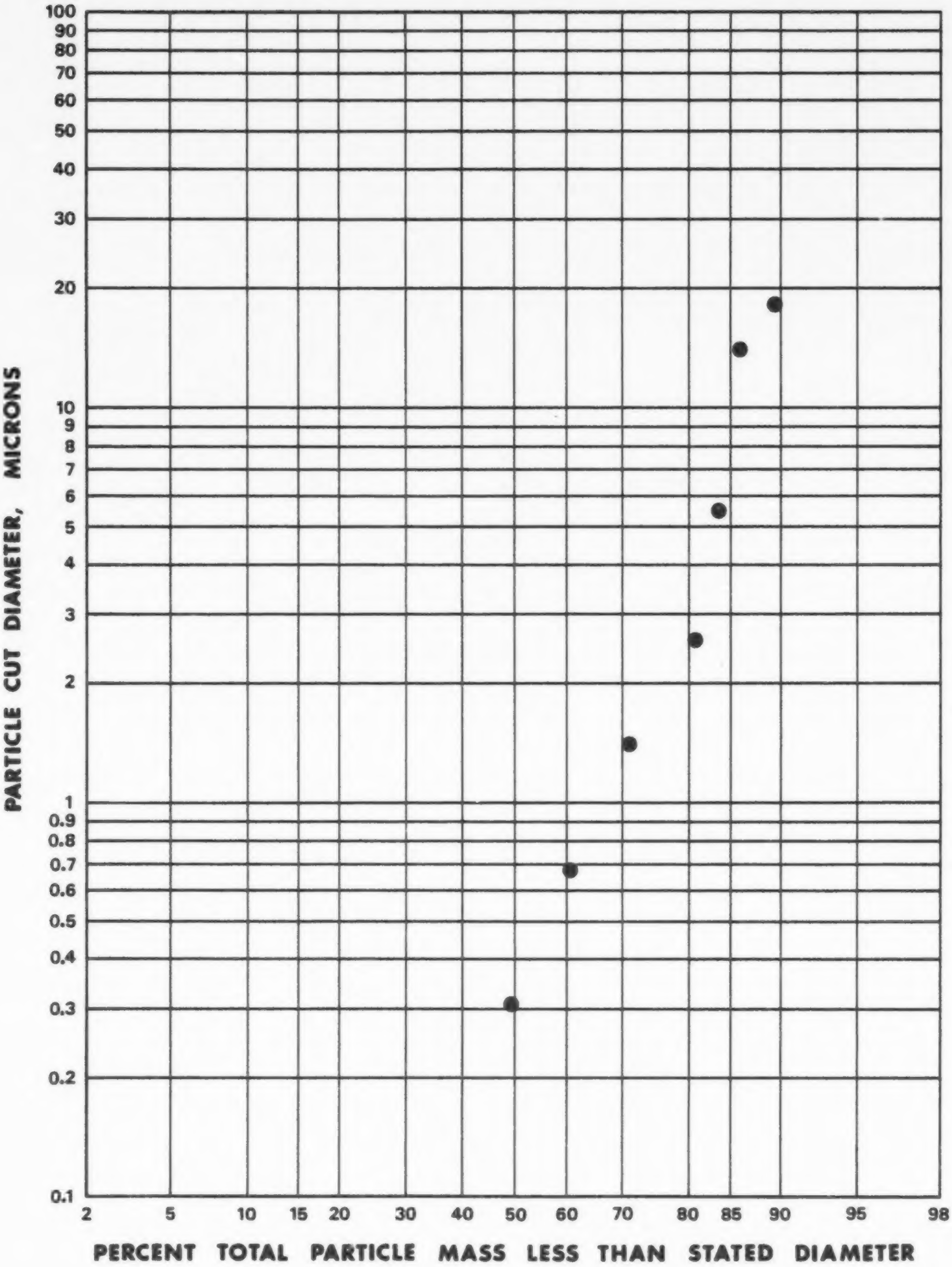

Figure 17. Particle size distribution, Run 41, AN-3.

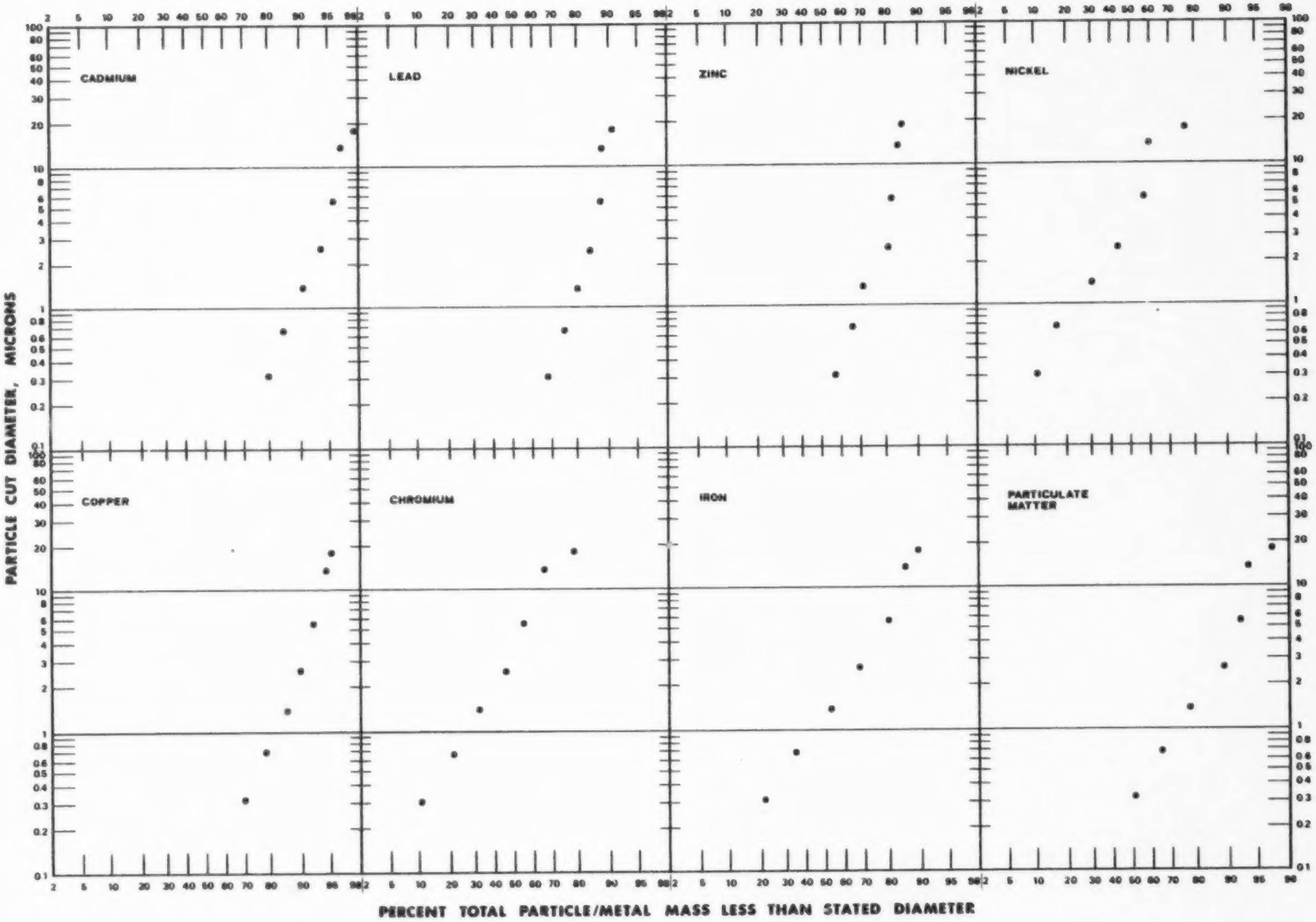

Figure 18. Particle/metal size distributions, Run 41, AN-4.

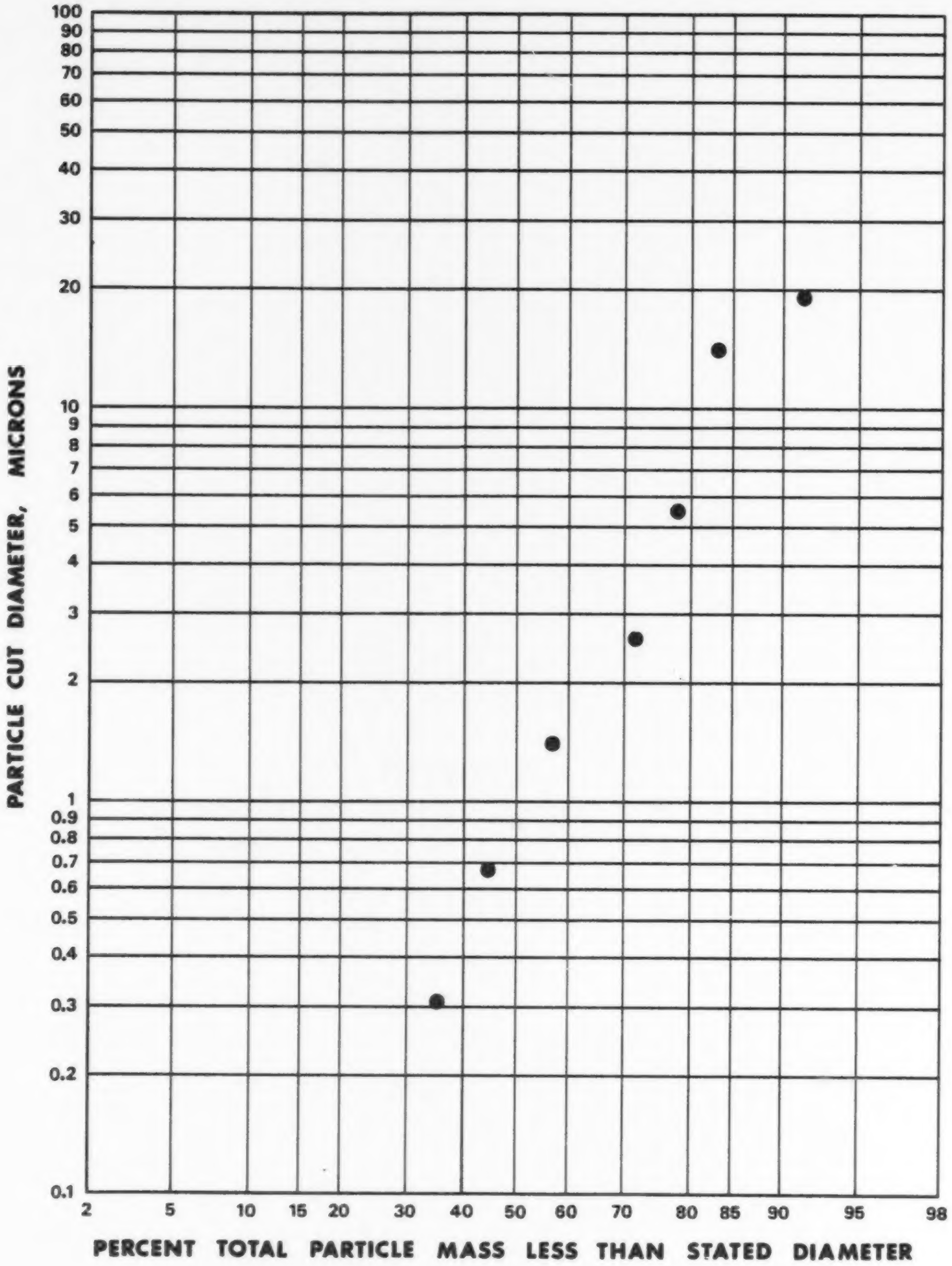

Figure 19. Particle size distribution, Run 42, PT-3.

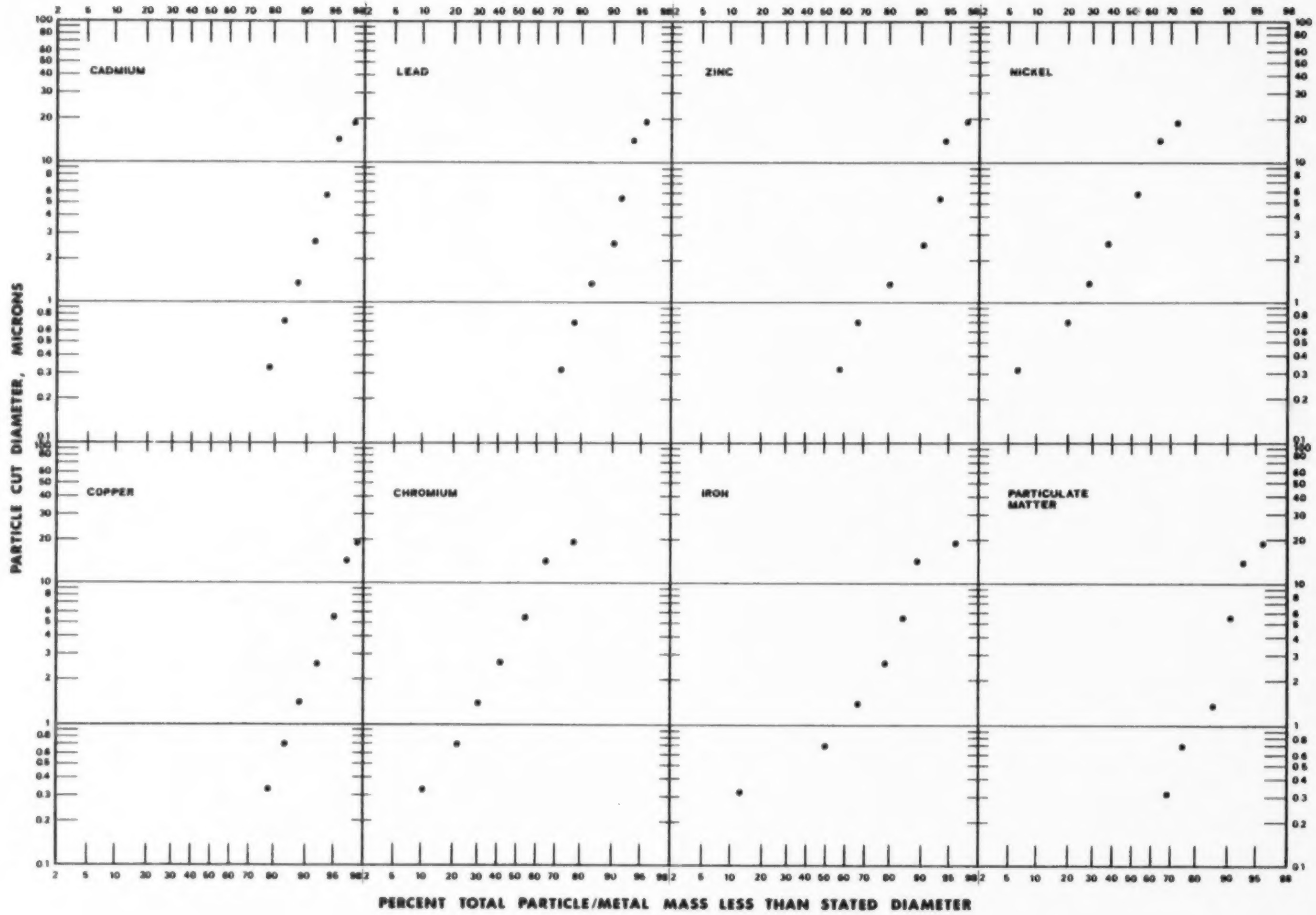

Figure 20. Particle/metal size distributions, Run 42, AN-5.

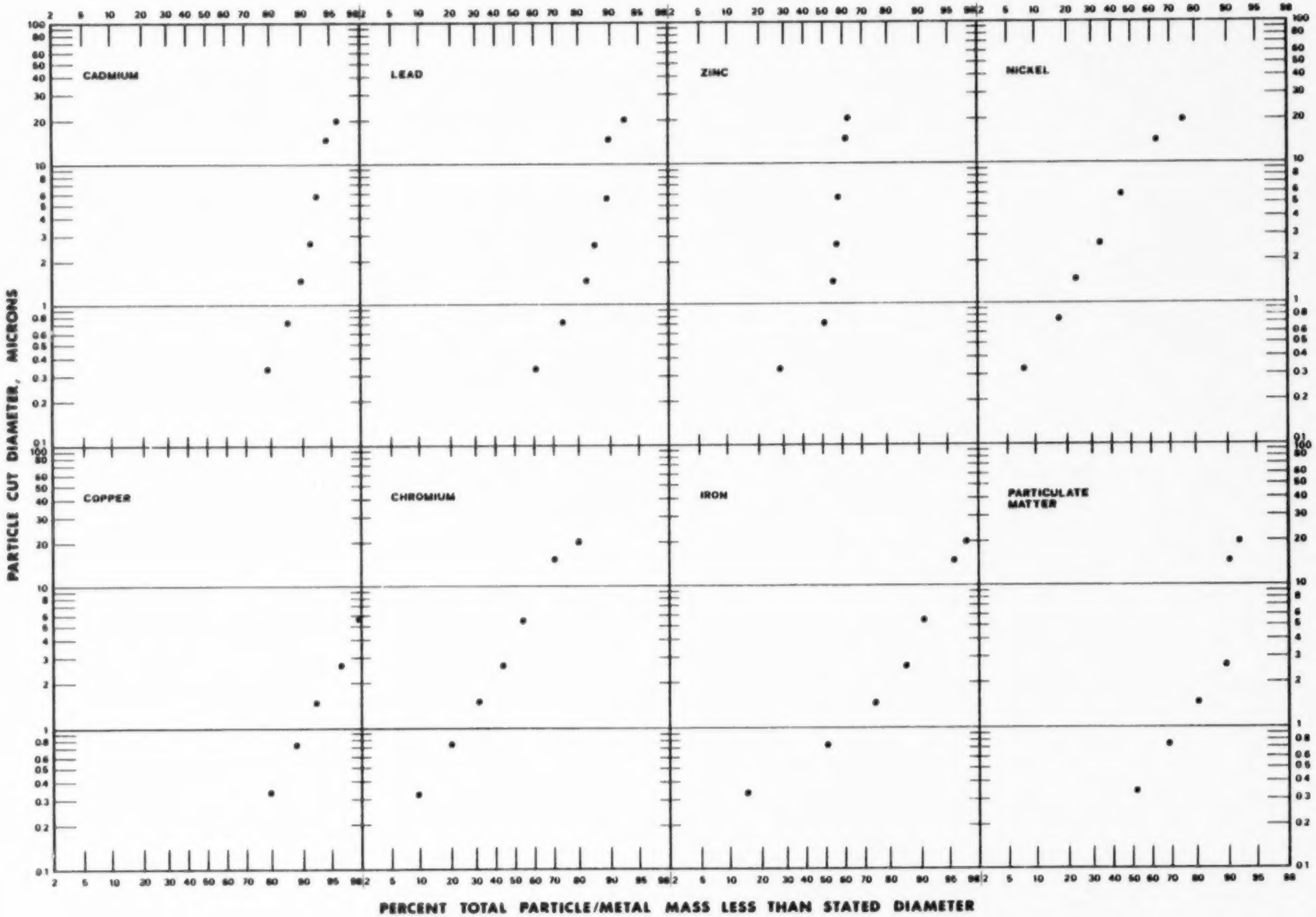

Figure 21. Particle/metal size distributions, Run 42, AN-6.

SECTION 5

DISCUSSION

A discussion of the experimental results is presented in this section in five parts: evaluation of gasifier performance, particle and gaseous emissions, metals balance, utilization of x-ray fluorescence for metals determinations, and particle and metal size distribution.

EVALUATION OF GASIFIER PERFORMANCE

An evaluation of the performance of the gasifier during Runs 33, 36, 37, 38, 40, 41, 42, 44 is presented in three parts dealing with operating parameters, producer gas quality, and energy balances.

Operating Parameters

Operating parameters that affect the performance of the gasifier significantly are air input rate, gasification rate, internal gasifier temperatures, slag formation, and fuel flow characteristics.

Air input rate - The air input rate is the most easily controlled parameter in the gasification process. In the absence of changes in the fuel composition and gasifier dimensions, the air input rate directly affects the gas output rate, gasifier reaction zone temperatures, gas outlet temperatures, producer gas composition, and slag formation. For the gasifier runs discussed in this report, it was decided to maintain a constant air input rate. The air input rates for the 8 gasifier runs varied between 1.92 and 2.01 m^3/min @ 20°C, 1 atm (see Table 9).

Gas output rate - The gasification rate is defined to be the rate at which producer gas is generated. To compare gasifiers of different size, an operational parameter called the specific gasification rate is used. The specific gasification rate is defined to be the gas output rate divided by choke plate opening area. Specific gasification rates for Runs 36, 37, 38, 40, 41, 42, 44 are .809, .762, .674, .809, .757, .748, .764 $Nm^3/hr.cm^2$ (normal conditions are 1°C and 1 atm. pressure). Kaupp et al. (21) reported than an upper limit of $1Nm^3/hr.cm^2$ has been established for small downdraft gasifiers using wood fuels.

A graph showing the normalized specific gasification rates as a function of fuel ash content is presented in Figure 22. Each specific gasification rate was normalized to a common air inlet flowrate (Run 44). The data presented in Figure 22 show that the specific gasification rate of sludge/wastepaper is inversely proportional to the fuel ash content. Because the reactivity of wood fuels is higher than that of sludge/wastepaper fuels, and because the fuel ash content of wood fuels is lower than that of sludge/wastepaper fuels, the maximum specific gasification rate for sludge/wastepaper fuels should be less than that of wood fuels.

It is advantageous to operate the gasifier at a high specific gasification rate. The most obvious advantage is that the cost of the gasifier is minimized if operated close to its maximum gas output. A gasifier operated at a high specific gasification rate will maintain a high reactor temperature which is necessary to maintain a producer gas of good quality.

The maximum specific gasification rate (MSGR) can be determined theoretically by knowing the chemical composition of the fuel. The MSGR for wood occurs at an equivalence ratio of 0.225 (30). The equivalence ratio (ER) is defined as the oxidant to fuel weight ratio divided by the stoichiometric ratio. Because there are many factors that influence the gasification rate, theoretical determinations of the MSGR are at best a good initial estimate of the actual MSGR.

The actual MSGR can be determined by observing several changes that occur in the gasification process. As more air is added to the gasifier, the reaction zone expands. The MSGR corresponds to the gasification rate at which the reaction zone no longer expands. Further addition of air will push the gasification reactions towards combustion reactions, causing increases in the CO_2 concentration and gas temperature, and decreases in the CO and total hydrocarbon (THC) concentration. This change influences the air/fuel ratio, fuel consumption rate, gas composition and gas outlet temperature.

Internal gasifier temperatures - The gasifier reaction zone temperature affects all aspects of the gasifier performance. Two thermocouples were utilized to estimate the reaction zone temperature of the gasifier; "reduction zone" thermocouple and "lower reduction zone" thermocouple shown in Figure 3. Because the gasification reactions that occur in the gasifier are heterogeneous, chemical reactions take place either at the surface of the fuel particle, or in a very thin boundary layer that surrounds fuel particle. Thus the reaction temperature would be the surface temperature of the particle (14). The temperatures obtained by thermocouple measurements are gas phase temperatures, (with radiation, convection, and conduction errors) and not surface temperature measurements. Therefore, the "reduction zone" and "lower reduction zone" temperatures can be used only as relative measures of the fuel bed temperature and not the actual reaction zone temperature.

The variation in the reduction zone and lower reduction zone temperatures during Runs 40, 41, 42 is presented in Figures D-8, D-14, D-20, and D-26 in Appendix D. Note that after the gasifier is "warmed up", both the reduction zone and lower reduction zone temperatures are relatively constant; about 970°C and 790°C respectively.

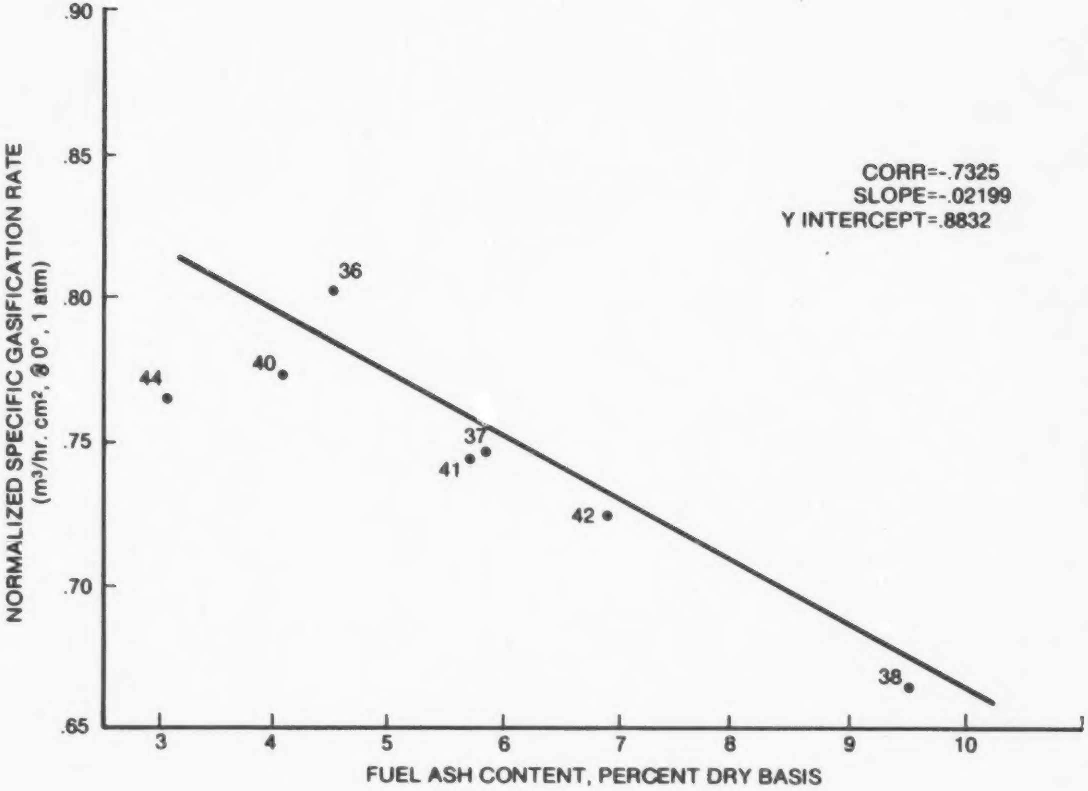

Figure 22. Variation of the normalized specific gasification rate with fuel ash content. Specific gasification rates normalized to Run 44 air inlet flowrate.

High internal gasifier temperatures influence the gasification process in many ways: 1) tars, higher hydrocarbons and other products of fuel distillation in the gasifier are thermally cracked to non-condensible hydrocarbons in the hot partial combustion zone of the gasifier, 2) the chemical equilibrium for the formation of CO and H_2 is favored by high temperatures, 3) the tendency for the formation of slag is affected greatly by the internal gasifier temperature.

Slag formation - The formation of slag is one of the most critical parameters in the operation of downdraft gasifiers. Because the ash content of wastewater sludge is high (25-40 percent dry basis), pure sludge cannot be gasified in downdraft gasifiers without execssive slag formation. To make fuel useable in a downdraft gasifier, low ash wastepaper is mixed with the wastewater sludge. Because the economics of sludge/wastepaper favor high ash fuel (33), the maximum fuel ash content is an important parameter in sludge/wastepaper gasification in downdraft gasifiers.

Based on the results presented in Table 9, the highest slag generation rates occurred during Runs 33 and 38 using batch #4 fuel (the highest ash content fuel tested). The slag generation rates for the other fuels (batches #1, #2, #3; percent ash content: 4.1, 4.4, 6.4 respectively) were all significantly less than those for batch #4 fuel (percent ash content: 9.0).

After each gasifier run, the gasifier was taken apart to check for slag agglomerations that may have formed under the tuyeres and on the choke plate. Large slag agglomerations were found between the tuyeres and the choke plate during Runs 33 and 38 (batch #4 fuel). These agglomerations were found along the sides of an imaginary frustum (of a cone), made by the tuyere circle and the choke plate. Although the slag agglomerations found from Runs 33 and 38 were not blocking the flow of char through the gasifier, continuous operation with this fuel would probably cause blockage. Thus batch #4 fuel is not a suitable fuel for sludge/wastepaper gasification in a standard downdraft gasifier. Because no significant slag agglomerations were found from fuel batches #1, #2, #3, these fuels (ash content up to 6.9%, Run 42) for standard downdraft gasifiers. Groeneveld has modified standard downdraft gasifier designs and successfully gasified solid waste with an ash content of 26 percent (13).

Fuel flow characteristics - A problem commonly experienced in working with downdraft gasifiers is the inability of the fuel to flow through the gasifier. Because the fuel must flow through the gasifier by gravity and without mechanical assistance, the ability of the fuel to flow through the gasifier is very important to the trouble free operation of the gasifier. To eliminate blockages, or "bridges" in the fuel bed, downdraft gasifiers require a dense, uniformly sized fuel. The densified sludge/wastepaper fuels tested had satisfactory fuel flow characteristics.

Quality of Producer Gas

Although the primary purpose of this project is the disposal of sludge and wastepaper in an economic and environmentally acceptable manner, the production of energy from this process is critical to the economic feasibility of sludge/wastepaper gasification. Thus the quality and stability of the gas produced are important variables in assessing the success of the project.

The most important application of producer gas is in its conversion to mechanical energy using an internal combustion engine or a gas turbine. Producer gas that is to be used is engines and turbines must 1) have a relatively steady gas composition that is sufficient to sustain combustion, 2) have a low temperature, 3) have a minimum amount of tars, and 4) be free of particulate matter. Because the particulate matter in the producer gas is determined primarily by the clean-up equipment used rather than the operation of the gasifier, particulate matter in the producer gas is not discussed here.

A plots of producer gas composition variations throughout Runs 36, 37, 38, 40, 41, 42, 44 are presented in Appendix D. The producer gas composition is relatively constant throughout the gasifier run. (Wide variations in the THC concentrations is probably due to variation in the instrument calibration, see Section 3.) However, when the gasifier was shut down, there were large discontinuties in the producer gas composition data. In some cases the CO, H_2, THC concentrations increased. This increase is due to the continuation of gasification and pyrolysis reactions with the residual heat in the gasifier. Because N_2 (in air) is not injected into the gasifier bed during shutdown, the concentrations of pyrolysis and gasification reactions is much higher.

In some cases all producer gas concentrations drop. This was due to N_2 purging of the producer gas analysis instruments during gasifier shutdown. Thus the instruments did not "see" the products present in the gasifier during shutdown. Obviously, peaks and valleys due to gasifier shutdown would not occur with continuous operation.

The three gaseous constitutents that make up the combustible fraction of the producer gas are CO, H_2, and total hydrocarbons (THC). Based on producer gas analyses from the gasification of sludge/wastepaper fuels, the THC fraction was found to contain about 70 percent CH_4 and about 30 percent C_2H_4. The major combustible fraction of the producer gas is made up of CO and H_2. The following chemical equations can be used to describe the formation of CO and H_2 in the gasifier:

(Boudouard reaction) $C + CO_2 = 2CO$ - 172,600 kJ/kg mole
(water gas reaction) $C + H_2O(gas) = CO + H_2$ - 131,400 kJ/kg mole

Because both the Boudouard reaction and the water gas reaction are strongly endothermic, the production of large amounts of CO and H_2 occurs at high gasifier temperatures.

Because the energy contents of CH_4 and C_2H_4 (THC) are much greater than the enegy contents of CO and H_2, the THC concentration influences greatly the overall energy content of the producer gas. The formation of CH_4 can occur by two different chemical mechanisms in the gasifier. The first mechanism for CH_4 production occurs in the distillation zone where gases (including CO_2, CO, CH_4, C_nH_{2n}), tars, pyroligneous acids, light and heavy oils, and water vapor are produced. Though the production of CH_4 and other non-combustible hydrocarbons resulting from the distillation process is desired, the presence of tar vapor that accompany these gases creates many problems in a gasifier system. If tar laden producer gas is used in an engine or gas turbine, valves and other internal parts will become gummed quickly. Therefore tar vapor in the producer gas cannot be tolerated when used to fuel engines or gas turbines.

A gasifier that requires extensive tar removal is unacceptable for two reasons. First, the extraction of tar vapor is difficult and expensive. Second, the tar has the highest heating value of all combustible products obtained from the gasification of organic matter (21). It is therefore desirable to thermally crack the tars into non-condensible hydrocarbons and other products. Thermal cracking of tars is accom-plished when tars from pyrolysis reactions pass through the hot bed of carbon in the partial combustion zone. Because the high temperatures in the partial combustion zone are caused by exothermic combustion reactions involving air and fuel, if the air cannot penetrate into the fuel bed, there will be cold spots. These cold spots in the fuel bed will allow tars to pass through the partial combustion zone (and thus from the gasifier) uncracked. The placement of tuyeres and the width of the gasifier are critical for the design of gasifier which produce tar free gas.

The second mechanism by which CH_4 is produced in a gasifier is via a weakly exothermic reaction:

$$C + 2H_2 = CH_4 + 75{,}000 \text{ KJ/kg mole}$$

The production of CH_4 with the above reaction is favored by low temperatures and high pressures. Thus a trade-off between high CH_4 production and low producer gas tar content exists. Because of the problems associated with tar vapor removal a producer gas with a low tar content is prefered for small installations.

Energy Balances

Mass and energy balances for Runs 36, 37, 38, 40, 41, 42, 44 are presented in Table 10 in Section 4. The most important energy balance parameter is the cold gas efficiency which represents the percent input fuel converted to chemical energy (evaluated using lower heating values) as producer gas. The cold gas efficiency results in Table 10 varied between 84.58% to 52.35%. However, because the large mass balance uncertainties in Runs 36, 37, 40, the cold gas efficiencies are abnormally high and should not be considered accurate. Based on previous sludge/wastepaepr gasification work (33), cold gas efficiencies range between 43 and 72 percent while Williams et al. (39) report cold gas efficiencies for agricultural residue fuels between 58 and 86 percent.

For energy conversion operations which require a clean, cool gas (internal combustion engines, gas turbines) the cold gas efficiency should be used as the conversion efficiency. However, the hot gas efficiency can be used as a conversion efficiency if the sensible energy of the producer gas can be utilized in the process, such as in a boiler.

PARTICLE AND GASEOUS EMISSIONS

Particle emission tests using EPA Reference Method 5 were conducted for Runs 36, 37, 38, 40, 41, 42, gaseous emissions were measured during Runs 36, 37, 38, and particle size distribution tests were performed during Runs 40, 41, 42. A discussion of the particle and gaseous emission tests is presented below. Particle size distributions are discussed later in this section.

Particle Emissions

A summary of the particle emissions results is presented in Table 11. The particle emissions concentration varied between 35.70 mg/DSCM (milligrams per dry standard cubic meter, 20°C, 1 atmosphere pressure) and 192.96 mg/DSCM, corrected to 12% CO_2. The federal standard for particle emission rates from incinerators is 189 mg/DSCM corrected to 12 percent CO_2. Thus federal standards for particle emissions were met in all cases except for Run 36, without the use of any clean-up equipment. Though the level of particle emissions is dependent on the design of the burner or boiler, it can be inferred that gasifiers in the boiler application can easily meet federal particle emissions standards with minimal clean-up equipment.

Gaseous Emissions

A summary of the gaseous emission test results for O_2, CO_2, CO, THC, NO_x, SO_2 Table 12. The CO concentrations ranged from 15.1 to 16.8 ppm, THC concentrations ranged between 1.39 and 12.7 ppm, NO_x concentrations ranged from 98.6 to 121 ppm, and SO_2 concentrations ranged between 55.5 and 105 ppm. There are no federal CO, THC, NO_x and SO_2 emissions standards for incinerators.

METALS BALANCE

An evaluation of the metals balance experimental results based on atomic absorption spectrophotometry is presented below in three parts; enrichment factors, volatile metals, and matrix metals. Metals balance results using x-ray fluorescence is also discussed.

Enrichment Factors

Enrichment factors are useful parameters for the comparison of char, fly ash, and emissions metals composition to fuel metals composition. Enrichment factors correct for increases in metal concentration due to carbon losses by normalizing the sample and the fuel with an ash matrix constituent, Coles et al. (4) recommended normalizing with a rare earth element while Law et al. (23) normalized ash, fly ash, and emissions particles with respect to iron. Enrichment factors presented in this report were normalized with respect to iron according to the following formula:

$$EF = \frac{[M]/[Fe]\ \text{sample}}{[M]/[Fe]\ \text{fuel}}$$

where $[M]$ = concentration of metal M in ppm

$[Fe]$ = concentration of iron in ppm

"Sample" in the formula above represent either char, fly ash, or emissions particles. Because iron is a constituent of the ash matrix, enrichment factors are useful in the study of the behavior of metals in the gasification process. If $ER \geq 1$ it can be concluded that the metal is not part of the ash matrix and was deposited on the sample during the gasification process. If ER=1, the metal is an ash matrix, and if $EF \leq 1$, the metal was transported away from the sample through volatiziation. Enrichment factors for char, fly ash, and emissions particles are presented in Figures 23, 24, and 25 respectively.

Volatile Metals

Volatile metals for this study were cadmium, lead, and zinc. The percent closure for cadmium, lead, and zone was presented in Section 4 in Figures 8, 9, and 10. Run 40 has the highest closure percentage followed in order by Runs 37 and 42, Runs 33 and 38, and Runs 36 and 41, for all three metals. This trend indicates the fraction of metals unaccounted for is due to inaccurate fuel concentrations (see sampling methods, Section 3). Figures 8, 9 and 10 also show the fractions of the metals found in the char, fly ash, and burner emissions are independent of fuel concentration, within the concentration range of this study. This result is important because the behavior of metals can be predicted from sludge concentrations other than those used in this study.

Char - The fraction of cadmium found in the emissions was greater than the fractions of lead and zinc (in order). Because of its high volatility the concentration of cadmium in the char was lower than the concentration of zinc and lead in char. Based on the vapor pressure data, all of the volatile metals could be vaporized at the temperatures in the gasifier reduction zones (958 to 1011°C). The fact that there are considerable amounts of Cd, Pb and Zn in the char suggests the metals behavior is dependent on factors other than simply temperature. The enrichment factors for the char were all less than one for the volatile metals. Cadmium had EFs ranging from 0.14 to 0.30, lead had EFs ranging from 0.29 to 0.58, zinc had EFs ranging from 0.38 to 0.63 for the char. The EF values indicate Cd, Pd and Zn were transported out of the gasifier in the producer gas.

Fly ash - Prior to combustion, particulate matter was removed from the producer gas stream by a high efficiency cyclone designed to recover particles greater than 10 micrometers. Because the mass of fly ash collected is about 5 percent of the mass of char collected, the fly ash contained less total metals than the char. But, the fly ash contained higher concentrations of volatile metals than the char, which indicates that the volatile metals were absorbed on the fly ash particles between the gasifier and the cyclone.

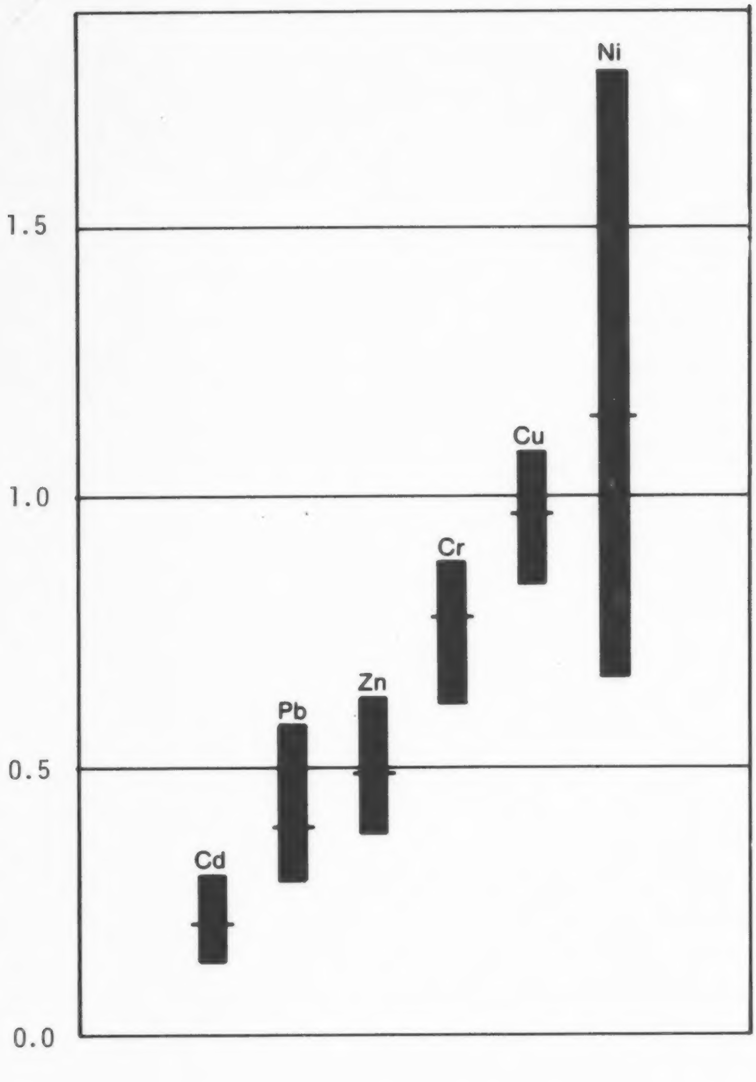

Figure 23. Enrichment factors for metals in char. Bar represents all values, horizontal line is mean value.

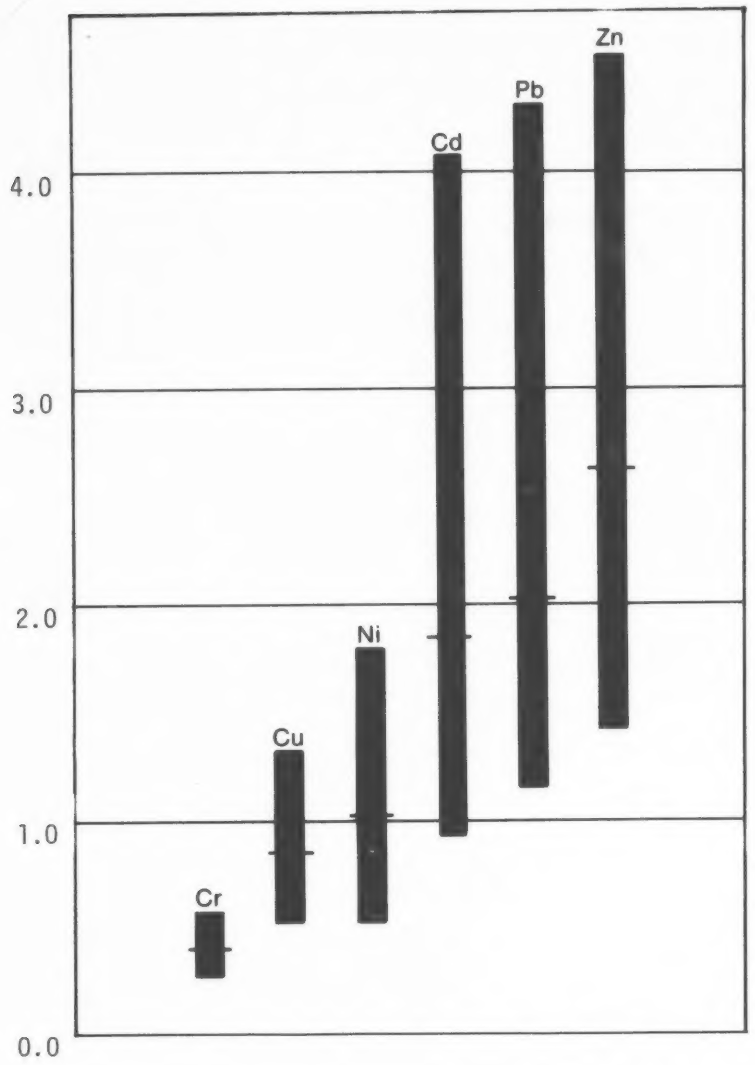

Figure 24. Enrichment factors for metals in fly ash. Bar represents all values, horizontal line is mean value.

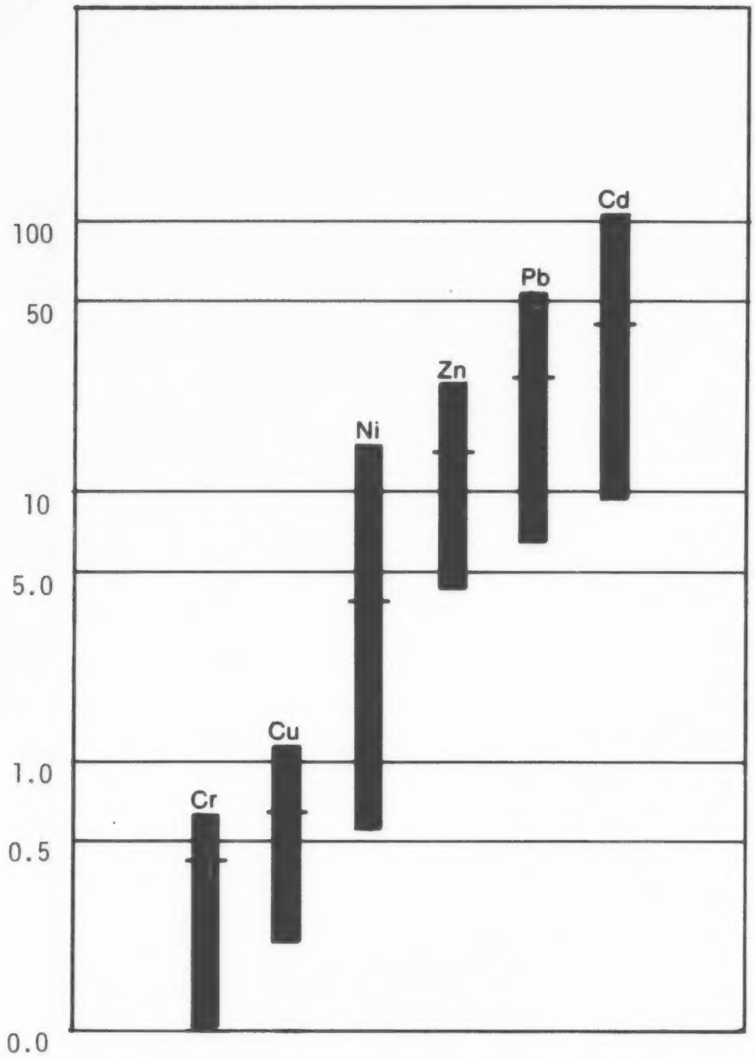

Figure 25. Enrichment factors for metals on Method 5 filter. Bar represents all values, horizontal line is mean value.

Note that the temperature in the gasifier is about 1000°C while the gas temperature at the cyclone is about 600°C.

The producer gas takes (on the average) less than 1/10 second to travel from the gasifier reduction zone to the cyclone. Thus condensation of volatile metals on the fly ash particles occurs very rapidly. The turbulent conditions that exist in the pipe (Re = 98,000) contribute to the deposition of metals on particulate matter by increasing the mixing of metal vapors and particulate matter. Because volatile metals condense on particles at lower temperatures, volatile metals can be removed from gas stream (and therefore from burner emissions) with a wet scrubber, which both cools the gas and removes particulate matter.

Based on the enrichment factor results presented in Figure 24, EF Zinc ≥ EF lead ≥ EF cadmium. The enrichment factors for zinc, lead, cadmium, on fly ash ranged between 1.4 to 4.6, 1.1 to 4.3 and 0.9 to 4.1. Although condensation of volatile metal vapor does occur between the gasifier and the cyclone, the condensation measured experimentally does not correlate well with the volatile metal vapor pressure data. Vapor pressure data predict that ER cadmium ≥ ER zinc ≥ ER zonc. Therefore a model to predict concentrations of metal vapor based on metal vapor pressure data alone is inappropriate for sludge/wastepaper gasification.

Previous work has shown cadmium volatizes to a greater extent at lower temperatures than zinc or lead during sludge incineration (12). The greater enrichment of zinc in the fly ash can be due to the fact that at the cyclone the producer gas is still hot enough that volatilized cadmium and lead compounds are not condensing on the fly ash particles. Coles et al. (4) calculated enrichment factors for coal fly ash at median diameters of 18.5μm and 6.5μm and found the EF for lead (1.4/0.1) was greater than the EF for zinc (1.0/0.2) which was greater than the EF for cadmium (0.4/0.2). Comparisons of enrichment factors from other studies are inappropriate due to the variety of fuels used and the methods for calculating enrichment factors, but qualitative comparisons are useful. Laws and Gordon's (23) work on municipal solid waste incinerator fly ash also showed lead enrichment greater than zinc, greater than cadmium. The results of this study (EF zinc ≥ EF lead ≥ EF cadmium) do not agree with the work of Law and Gordon (23), and Coles et al.(4).

Particle emissions - Particle emissions and volatile metals were collected on 1.0μm Zefluor filter using an EPA Method 5 sample train. Method 5 probe will collect particulate matter and volatile metals in three areas; a) before the filter in the probe; b) on the filter, and c) after the filter in the impinger. Based on the results, summarized in Figures 8, 9, 10, a substantial fraction of the volatile metals entering the gasifier were recovered as particle emissions at the burner. Because the metal concentration of particle emissions is dependent on the metal concentration of the fuel, it is not appropriate to compare the particle emissions metal concentrations from this study with those of other studies.

The percentage of volatile metals collected before the filter varied between 0.4 and 13.7 percent for cadmium, 0.1 and 2.6 percent for lead, and

0.1 and 4.3 percent for zinc. The volatile metals were detected before the filter in the probe due to the condensation of metal vapors in the stack on the relatively cool walls of the probe.

The percentage of volatile metals collected on the filter varied between 37.4 and 63.0 percent for cadmium, between 23.0 and 42.7 percent for lead, and between 11.6 and 21.8 percent for zinc. Metals collected on the filter were assumed to be associated with particulate matter. However, there is a possibility that some metal vapor was condensed on the filter, which was kept at 121°C.

A very small fraction of volatile metals was found after the filter for all runs except Run 33. (Because the Method 5 filter was not properly seated during Run 33, the fraction of metals found after the filter was high. The by-passed filter did not affect the overall particle emissions.) To aid in the collection of metal vapors, 3M HCl was added to the first impinger of the Method 5 sample train for Runs 40, 41, 42. Only trace quantities of the volatile metals were found after the filter leading to the conclusion that either the metals were associated with particles and captured by the filter or the metals were on such small particles that they never contacted the acid in the condenser. The latter hypothesis seems unlikely due to the fine bubbles created by the impinger and the Brownian motion of the small particles inside the gas bubble.

The enrichment factors presented in Figure 25 were calculated for emissions based on metal concentrations found on the filter only; not the before and after filter catch. Of the volatile metals, cadmium had the greatest degree of enrichment, followed by lead and zinc. The order is opposite to that found for the fly ash; Zn $\geq$ Pb $\geq$Cd. Variations in the enrichment factors for each metal reflect the range of metal concentrations calculated for the particle emissions.

Because the particles captured on the filter were less than 10μm, diameter comparisons to enrichment factor work by Coles et al.(4), can be made. For particles less than 10μm Coles et al. found zinc to have a greater EF than lead which was in turn greater than cadmium. Law and Gordon (23) found lead to have a greater EF than zinc which was greater than cadmium. Bennett and Knapp (2) found cadmium to have the largest EF, followed by zinc and lead, respectively. Greenberg et al. (11) found EFs of cadmium greater than lead, greater than zinc. Clearly, the work reported in the literature does not favor one volatile metal over another as the most enriched on small particles.

Non-volatile Metals

Copper, chromium, iron, and nickel have all been classed as non-volatile in previous studies on sludge incinerators and coal fired power plants. Because nickel exhibited uncharacteristic behavior during the gasification process, it will be discussed separately following the other non-volatile metals.

The closures presented for Cu, Cr, and Fe in Figures 11, 12, and 13, respectively exhibit the same trends as the volatile metals. The fraction of each metal unaccounted for is due to inaccurate fuel concentrations. Based on Figures 11, 12, 13, the percentages of each metal found in each gasifier stream were independent of the fuel concentration, within the fuel concentrations of this study, with the exception of the slag, which increases with increasing sludge concentration.

Char - All three non-volatile elements behaved as ash matrix elements in that nearly all of the fuel metal could be accounted for by the char. These results are supported by the work of Takeda and Hiroaka (36); and Law and Gordon (23). The enrichment factors for the non-volatile metals in the char ranged from 0.84 to 1.08 for copper, and 0.62 to 0.88 for chromium.

The concentrations of the metals for the duplicate runs were very close to one another. Again the concentration of the metal in the char was dependent on the concentration in the fuel since the percentage in the char remains nearly constant.

Fly Ash - The fly ash collected in the cyclone contained concentrations of non-volatile metals very near those of the char for each gasifier run. This is due to the fact that the non-volatile elements are ash matrix constituents and the concentration will change if the amount of carbon present changes. Based on the ultimate analysis data for the char and fly ash presented in Tables 6 and 7 and it can be seen that the amount of carbon in the fly ash is very near that of the char. Thus, there is essentially no change in the concentration of the ash matrix constituents. The enrichment factors for the fly ash ranged from 0.54 to 1.34 for copper, and 0.28 to 0.57 for chromium.

Emissions - The producer gas burner emissions contained only traces of the non-volatile metals. The amounts of non-volatiles recovered in the burner emissions ranged from 1.0 to 4.6 percent for copper, 0.7 to 2.9 percent for chromium, and 0.7 to 4.0 for iron. The enrichment factors ranged from 0.21 to 1.15 for copper, and 0.06 to 0.63 for chromium. (Enrichment factors for iron cannot be calculated as iron is the normalizing element.) Thus there was essentially no enrichment of non-volatile (matrix) elements onto small particles.

Slag - The non-volatile metals are found in very high concentrations in the slag since they are part of the ash matrix and slag is almost entirely ash. As being part of the ash matrix, the amount of non-volatile metals recovered is dependent on the amount of slag formed during the gasifier run, which depends on the amount of sludge in the fuel. As shown in Figures 11, 12, and 13, the percent non-volatile metals increases with the metals concentration of the fuel.

Nickel - Although the percent closure for nickel are sporadic, the data presented in Table 14 can be used to explain the behavior of nickel during the gasification process. The concentration of nickel in the char and fly ash are very similar for each run. Based on the ultimate analysis data presented in Tables 6 and 7, the fly ash and char have very similar residue and carbon concentrations. Therefore it can be concluded that an element, in the same concentration in both the char and fly ash, is part of the ash matrix. The concentrations of the remaining matrix elements did not vary between the char and fly ash, while the volatile elements concentrations were several times higher in the fly ash than in the char.

In Runs 33 and 37, the behavior of nickel was not that of a matrix element. The nickel concentration in the fly ash is significantly higher than the nickel concentration in the char by approximately 15 percent. The nickel concentration in the emissions was higher than for any Run except Run 37. Although, during Run 37, the concentration of nickel in the fly ash was 25 percent lower than that of the char, a very large amount of nickel was found in the emissions. Therefore, based on nickel mass balances for five gasifier runs (Runs 36, 38, 40, 41, 42), nickel could be characterized as a matrix element. Based on the nickel mass balances for Runs 33 and 37, nickel acts as a volatile element, but not to the same degree as cadmium, lead, or zinc.

USE OF X-RAY FLUORESCENCE FOR METALS DETERMINATIONS

X-ray fluorescence (XRF) analysis was used in addition to atomic absorption spectrophotometry (AAS) to analyze metals concentrations in gasifier samples generated during Run 33. A summary of metals concentrations for Run 33 data and the NBS fly ash using XRF is presented in Table 20. It is immediately apparent that there are many more metals analyzed using XRF than for AAS.

The obvious advantage that XRF has over AAS is that metals concentration data for several different metals can be generated from just one XRF sample. It would be advantageous to use XRF in place of AAS if the XRF results were sufficiently accurate. Because the accuracy of AAS for metals analysis was determined previously (Table 16), the accuracy of XRF metals analysis can be determined by comparing the metals concentration data from XRF and AAS analyses.

Based on this comparison, there was good agreement for XRF and AAS char lead concentrations and poor agreement in the fly ash lead concentrations. The lead concentrations in the slag and NBS fly ash samples were below the dectable limit of XRF. There was fair agreement for XRF and AAS char zinc concentrations. The XRF fly ash zinc concentration was as much as 400% more than the AAS fly ash zinc concentration. There was good agreement in the XRF and AAS zinc slag concentrations and poor agreement in the zinc NBS concentration. XRF underestimated the nickel concentrations in char, fly ash, and slag samples. Nickel in the NBS fly ash sample was below the dectable limit. There is good agreement between the XRF and AAS copper concentrations, and XRF overestimated chromium concentrations in char, fly ash, and slag samples. XRF was unable to detect chromium in the NBS fly ash sample.

Based on the results presented above, it appears that AAS produced much more accurate results than XRF. In addition, the error in the XRF results was in somecases ± 50%. The reason the XRF analyses were not as accurate as the AAS results was probably due to difficulties in XRF sample mounting. For

Table 20
UCD XRF ANALYSIS OF RUN 33 GASIFIER SAMPLES

Element	Metal Concentration, ppm							
	Char			Flyash			Slag	NBS[a] Sample
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3		
Sulfur	<31,730 <3600>	<10480 <3600>	<26550 <3600>	<15,800 <6500>	119,620 ±36,120 <6500>	<20,880 <6500>	<13,000	<11,520 [16,200 ± 300]
Potassium	8880 ±3580	6220 ±770	<9750	<5800	<12,870	3830 ±1890	7240 ± 920	5380 ±1120 [4200 ± 200]
Calcium	32,820 ±2440	23,600 ± 940	32,910 ± 2130	27,690 ±13600	6700 ±2000	18,030 ± 1360	46,970 ± 1430	5540 ± 670
Titanium	4020 ±1190	3820 ± 440	5130 ±1060	2020 ± 640	334,280 ± 6730	44,050 ± 1440	9230 ± 610	10,980 ± 610 [1800]
Vanadium	<1720	<610	<1450	<880	12,020 ± 4390	<1140	<820	<620 [44 ± 3]
Chronium	1860 ±260 (1040)	1330 ±120 (1040)	1550 ±240 (1040)	930 ±160 (740)	1600 ± 510 (740)	<560 (740)	2140 ±150 (1200)	<300 (34.1) [3.44 ± 1.5]
Manganese	1190 ±220	840 ± 100	940 ± 170	930 ± 130	<740	670 ± 130	1120 ± 100	220 ± 70 [28 ± 2]
Iron	(24,200)	(24,200)	(24,200)	(26,600)	(26,600)	(26,600)	(51,000)	(10,700) [11,100 ± 200]

Continued on next page

Table 20 (continued)

Element	Metal Concentration, ppm							
	Char			Flyash			Slag	NBS[a] Sample
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3		
Nickel	<290 (290)	<100 (290)	<240 (290)	<160 (334)	<320 (334)	<190 (334)	150 ± 50 (384)	<100 (20.1) [19.4 ± 1.0]
Copper	1230 ±120 (1020)	1020 ±150 (1020)	1230 ±100 (1020)	1280 ± 80 (1380)	1090 ±110 (1380)	1440 ± 80 (1380)	1790 ± 50 (1800)	< 90 (18.0) [16.5 ± 1.0]
Zinc	990 ±120 (943)	1110 ± 50 (943)	1280 ±100 (943)	13,060 ± 270 (8510)	33,810 ± 690 (8510)	14,360 ± 320 (8510)	360 ± 50 (304)	410 ± 40 (30.1) [28 ± 2]
Arsenic	<120	<50	<100	<80	510 ±110	<80	<50	<40 [9.3 ± 1.0]
Lead	<560 (132)	170 ±20 (132)	190 ±50 (132)	2390 ± 80 (1694)	1090 ±320 (1694)	2420 ±110 (1694)	<200 (97.5)	<200 (12.5) [12.4 ± 0.6]
Bromine	<150	20 1±20	<120	<80	<240	50 ±30	<50	40 ±10
Rubidium	<270	70 ±20	<220	<130	<450	<190	<100	100 ±20 [12.4 ± 0.6]

Continued on next page

Table 20 (continued)

Element	Metal Concentration, ppm							
	Char			Flyash			Slag	NBS[a] Sample
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3		
Strontium	490 ±70	310 ±20	440 ±70	290 ±50	NA	210 ±50	560 ±50	140 ±30
Molybdenum	310 ±190	<290	<750	270 ±110	<1600	<610	260 ±50	<720
Mass on XRF slide (mg)	0.50	1.05	0.55	0.20	0.90	0.55	0.75	0.75

( ) - Concentrations were determined by AAS

[ ] - Concentrations were determined by NBS

[a] NBS - 1632a coal sample

*Values obtained by NBS using a non-reference method

< > - Concentrations determined as part of ultimate analysis using Grote combustion method

<1000 - Upper limit of element not found by XRF is 1000 ppm

example, it was not possible to attach more than 2 mg on the XRF slide. It is difficult to get a representative sample in only 2 mg. In addition, it was impossible to confirm that the sample thickness on the XRF slide was uniform. Because the XRF detects metal mass per square centimeter, it is critical that the sample layer be of a uniform and known thickness. These criteria were impossible to check.

Therefore, based on the XRF sample mounting procedure described in Section 3 and the results presented above, XRF should not be used to quantify concentrations of metals. However XRF is an excellent method of analysis for determining what metals may be present in a sample.

PARTICLE AND METAL SIZE DISTRIBUTION

A tabular summary of the mass median aerodynamic diameter (MMAD) for particulate matters and metals is presented in Table 18. In addition, size distributions for each gasifier run are presented in Figures 14 through 21.

The enrichment of metals on small particles can be determined by comparing the particulate matter MMAD's with the metal MMAD's in Table 18. For example Cd and Pb have MMAD's less than (or equal to) particulate matter MMAD's, indicating metal enrichment on smaller particles. The enrichment of Zn on smaller particles supported by all data except for impactor run AN6. The enrichment of Cd, Pb, and Zn on smaller particles is consistent with the relatively high vapor pressure of these metals.

Based on a comparison of particulate matter and metal MMAD, it can be deduced that Ni, Cr, Fe are concentrated in the larger particles. As noted earlier these elements can be classified as matrix metals (metals not volatilized during combustion) and the Table 18 results are consistent with vapor pressure data for these metals.

Because the Cu MMAD is less than (or equal to) the particulate matter MMAD, the Table 18 results support the conclusion that Cu behaves as a volatile metal. Because this conclusion is not consistent with vapor pressure data, it may indicate a mechanism by which Cu is volatilized in the furnace and condensed on small particles.

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APPENDIX A

MASS AND ENERGY BALANCE COMPUTATIONS

A methodology and computer program, developed by Lamorey for fluidized bed gasifiers (22), was used to compute mass and energy balances for the sludge/wastepaper gasifier. The methodology of the mass and energy balance computations, presented below, is a summary from Lamorey's work (22). A listing of the mass and energy balance computer programs and outputs from Runs 36, 37, 38, 40, 41, 42, and 44 is presented in Appendix B.

Mass Balance Measurements

The following mass balance data were recorded during operation of the gasifier:

1. The combustion air volume flowrate was obtained from the time average of the pressure drop across an orifice plate in the air inlet line to the blower. The orifice plate was calibrated by using a portable venturi meter. During runs 36, 37, 38, and 44 the air inlet pressure drop measurements were taken at 5 minute intervals. For Runs 40, 41 and 42, static pressure and pressure drop readings were taken each minute using pressure transducers and the data acquisition system described in Appendix C. Plots showing the variation in the static pressure and pressure drop values throughout the gasifier run are presented in Appendix D.

2. The mass flow rate of the fuel was obtained by weighing the net fuel added to the gasifier during the run and dividing by the net run time.

3. The mass flow rate of the char was obtained by weighing the char before and after a run and dividing by the net run time. The mass flow rate of the fly ash was calculated similarly.

4. Representative fuel, char, and fly ash samples were taken for moisture content determination and ultimate analysis. Fuel, char, and fly ash composition data are summarized in Tables 5, 6, and 7.

5. Gas composition measurements in percent volume of dry gas at ambient temperature and pressure of CO, CO_2, H_2, and O_2 and THC (total hydrocarbon) were taken at 1 minute intervals using the data acquisition system described in Appendix C. Time averages of this data are presented in Table 8. Plots showing the variation of the producer gas composition throughout the gasifier run are presented in Appendix D.

6. The water vapor in the product gas was measured as part of the gas analysis system. As the hot producer gas passes through an ice bath condenser, glass wool filter, and molecular sieve pellets, water vapor and particulate matter were removed from the product gas. The mass collected was determined by weighing the condenser/filter system before and after the run. All mass collected in the condenser/filter system was assumed to be water. The volume of dry gas passing through the gas analysis system was measured by a dry gas meter just upstream of the gas analysis system. It was assumed that the dry gas volume was measured at 293°K.

Mass Balance Calculations

Mass balance values that were not measured were calculated by considering elemental and overall mass balances. Terms used in the mass balance calculations are described in Table A-1. The following method was used to analyze mass balance data.

1. An overall mass balance equates mass entering the gasifier as dry fuel, fuel moisture and the combustion air to mass leaving as char, fly ash, dry product gas, and water vapor in the gas. (Figure A-1 and Equation 1). The air mass flowrate is determined from the measured air volume flowrate and the ideal gas law by Equation 2. Determination of the char and fly ash rates have been described.

$$\dot{m}_f + \dot{m}_m + \dot{m}_a = \dot{m}_c + \dot{m}_g + \dot{m}_v + \dot{m}_p + \dot{m}_{fa} \qquad (1)$$

$$\dot{m}_a = \dot{V}_a \left(\frac{Pr}{RTr} \right) M_a \qquad (2)$$

balance (Figure A-2). The volume percent nitrogen in the dry product gas is determined by summing the percent CO, CO_2, THC, and H_2, then subtracting from 100%. The volume flowrate of the product gas is calculated from the nitrogen in the air and the nitrogen in the dry product gas by Equation 3 assuming the nitrogen content of air by volume is 79%. The molecular weight of the air and the product gas have been determined assuming that 1.3% of the nitrogen present is actually argon. Nitrogen in the fuel, char, and fly ash is present at less than 1% and is ignored. The dry product gas mass flowrate is determined from the volume rate and the ideal gas law (Equation 4).

Table A-1

LIST OF MASS BALANCE TERMS

Description of Term	Symbol
Volume flowrates (m^3/min	
air volume flowrate at 298°K, 1 atm. (orifice)	$\dot{V}_a$
dry product gas volume flowrate at 298°K, 1 atm. (derived)	$\dot{V}_g$
Mass flowrates (kg/hr)	
dry fuel (measured)	$\dot{m}_f$
water from fuel moisture (measured)	$\dot{m}_m$
combustion air (orifice)	$\dot{m}_a$
dry product gas (derived)	$\dot{m}_g$
water vapor in product gas (measured)	$\dot{m}_v$
char (measured)	$\dot{m}_c$
fly ash (measured)	$\dot{m}_{fa}$
Elemental mass flowrates (kg/hr)	
carbon in fuel	$\dot{m}_{fc}$
carbon in char	$\dot{m}_{cc}$
carbon in fly ash	$\dot{m}_{fac}$
carbon in product gas	$\dot{m}_{gc}$
hydrogen in dry fuel	$\dot{m}_{fh}$
hydrogen from water in fuel	$\dot{m}_{mh}$
hydrogen in dry product gas	$\dot{m}_{gh}$
hydrogen from water vapor in product gas	$\dot{m}_{vh}$
hydrogen in char	$\dot{m}_{ch}$
hydrogen in fly ash	$\dot{m}_{fah}$
oxygen in combustion air	$\dot{m}_{ao}$

Table A-1 (continued)

Description of Terms	Symbol
oxygen in dry fuel	$\dot{m}_{fo}$
oxygen from water in fuel	$\dot{m}_{mo}$
oxygen in dry product gas	$\dot{m}_{go}$
oxygen from water vapor in product gas	$\dot{m}_{vo}$
oxygen in char	$\dot{m}_{co}$
oxygen in fly ash	$\dot{m}_{fao}$
nitrogen in combustion air	$\dot{m}_{an}$
nitrogen in product gas	$\dot{m}_{gn}$
Mass fractions	
kg carbon in fuel per kg dry fuel	w_{fc}
kg carbon in char per kg dry fuel	w_{cc}
kg hydrogen in fuel per kg dry fuel	w_{fh}
kg oxygen in fuel per kg dry fuel	w_{fo}
kg water in wet fuel per kg dry fuel	w_{fm}
kg water vapor in wet product gas per kg dry product gas at temperature T	w_{gv}^{T}
Closure percentage	
carbon	C_c
hydrogen	C_h
oxygen	C_o
nitrogen	C_n
overall (mass)	C_m
Product gas volume (or mole) fraction	
m^3 of species i per m^3 of product gas	x_i
Molecular weight	
kg air per kg mole air	M_a

Table A-1 (continued)

Description of Term	Symbol
kg dry fuel per kg mole dry fuel	M_f
kg char per kg mole char	M_c
kg dry product gas per kg mole dry product gas	M_g
kg species i per kg mole species i	M_i
Other	
universal gas constant (= 8314.5 J/kg • mole • ^oK)	R
temperature of product gas at gasifier exit (^oK)	Te
reference temperature (= 298^oK)	Tr
reference pressure (= 1 atm)	Pr

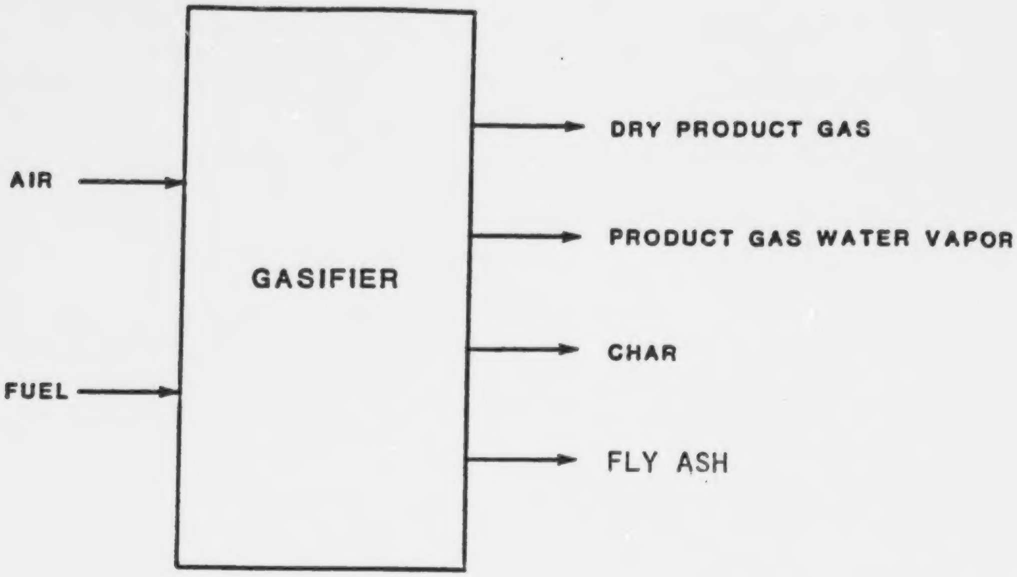
AIR
FUEL
GASIFIER
DRY PRODUCT GAS
PRODUCT GAS WATER VAPOR
CHAR
FLY ASH

Figure A-1. Overall mass balance.

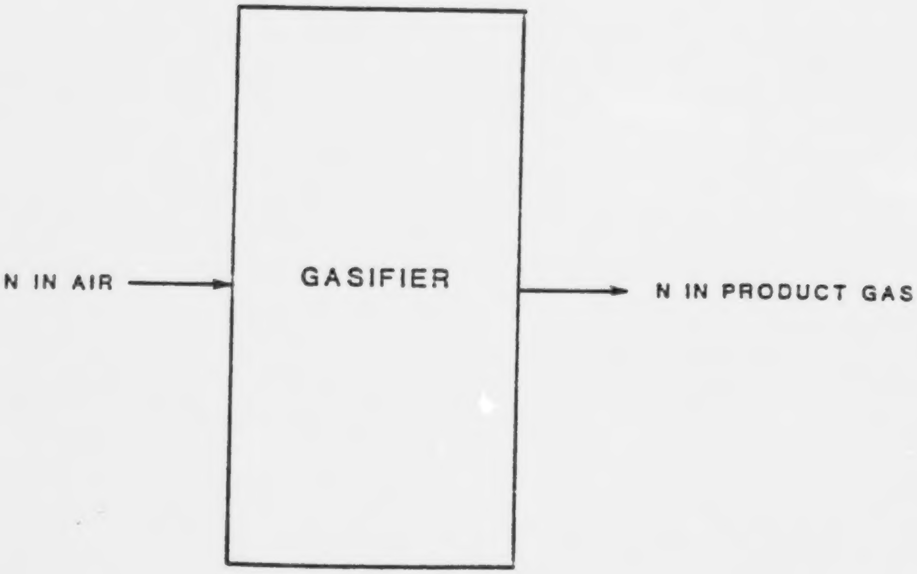
N IN AIR
GASIFIER
N IN PRODUCT GAS

Figure A-2. Nitrogen mass balance.

$$\dot{V}_g = \frac{0.79\ \dot{V}_a}{X_{N_2}} \qquad (3)$$

$$\dot{m}_g = \dot{V}_g \left(\frac{Pr}{RTr} \right) M_g \qquad (4)$$

3. The oxygen balance involves fuel rate, fuel moisture content, fuel oxygen content, air flowrate, dry gas flowrate, dry gas composition, char rate, fly ash rate, and gas water vapor (see Figure A-3).

4. The hydrogen balance involves fuel rate, fuel moisture content, fuel hydrogen content, dry gas flowrate, dry gas composition, char rate, fly ash rate, and gas water vapor (see Figure A-4). Hydrogen exiting as tar in the gas is neglected since no data are available on tar mass flowrate and composition.

5. The carbon balance involves dry fuel rate, dry gas rate, char rate, and fly ash rates (see Figure A-5). Carbon existing as tar in the gas and as solid particles not collected in the cyclone is neglected because no data are available on tar mass flowrate, tar composition,, and solid particle flowrate.

6. The percent closure for the carbon, hydrogen, oxygen, nitrogen, and overall mass balances is calculated using Equations 5, 6, 7, 8, and 9.

$$C_c = \left((\dot{m}_{fc} - (\dot{m}_{cc} + \dot{m}_{fac} + \dot{m}_{gc}) \div \dot{m}_{fc} \right) \times 100\% \qquad (5)$$

$$C_h = \left(\left(\dot{m}_{fh} + \dot{m}_{mh} - \dot{m}_{gh} - \dot{m}_{vh} - \dot{m}_{ch} - \dot{m}_{fah} \right) \div (\dot{m}_{fh} + \dot{m}_{mh}) \right) \times 100\% \qquad (6)$$

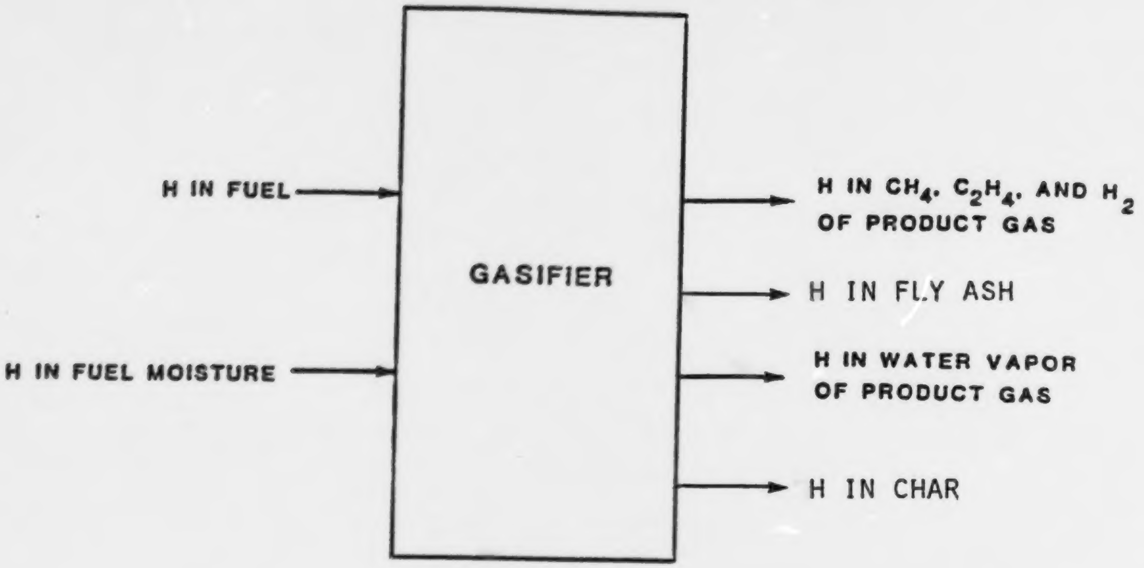
H IN FUEL
H IN FUEL MOISTURE
GASIFIER
H IN CH_4, C_2H_4, AND H_2 OF PRODUCT GAS
H IN FLY ASH
H IN WATER VAPOR OF PRODUCT GAS
H IN CHAR

Figure A-3. Hydrogen mass balance.

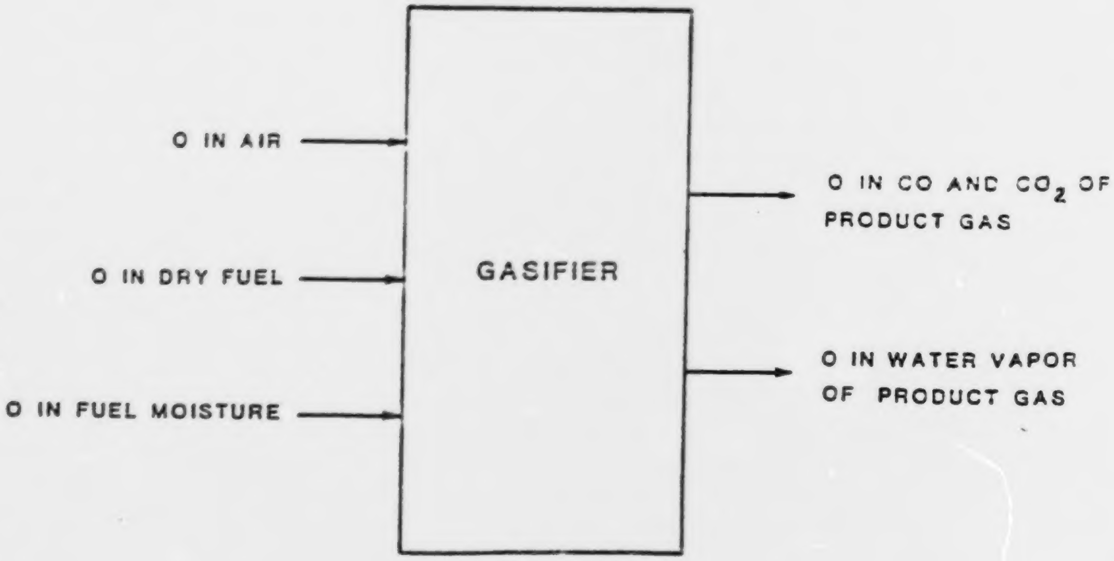
O IN AIR
O IN DRY FUEL
O IN FUEL MOISTURE
GASIFIER
O IN CO AND CO_2 OF PRODUCT GAS
O IN WATER VAPOR OF PRODUCT GAS

Figure A-4. Oxygen mass balance.

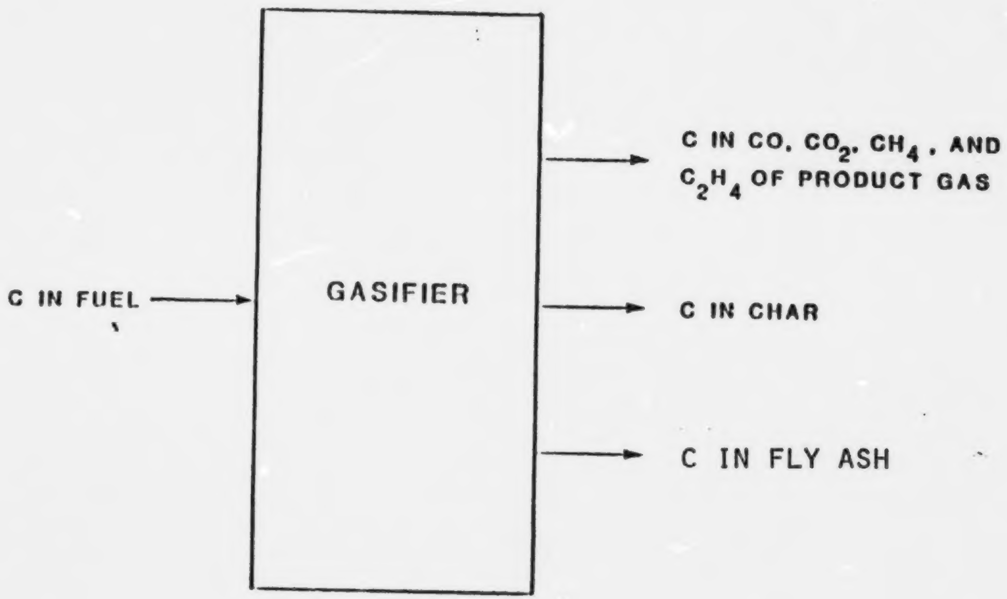
C IN FUEL
GASIFIER
C IN CO, CO_2, CH_4, AND C_2H_4 OF PRODUCT GAS
C IN CHAR
C IN FLY ASH

Figure A-5. Carbon mass balance.

$$C_o = \left[\left(\left(\dot{m}_{ao} + \dot{m}_{fo} + \dot{m}_{mo}\right) - \left(\dot{m}_{go} + \dot{m}_{vo} + \dot{m}_{co} + \dot{m}_{fao}\right)\right) \div \left(\dot{m}_{ao} + \dot{m}_{fo} + \dot{m}_{mo}\right)\right] \times 100\% \qquad (7)$$

$$C_n = \left(\left(\dot{m}_{an} - \dot{m}_{gn}\right) \div \dot{m}_{an}\right) \times 100\% \qquad (8)$$

$$C_m = \left[\left(\left(\dot{m}_f + \dot{m}_m + \dot{m}_a\right) - \left(\dot{m}_g + \dot{m}_v + \dot{m}_c + \dot{m}_{fa}\right)\right) \div \left(\dot{m}_f + \dot{m}_m + \dot{m}_a\right)\right] \times 100\% \qquad (9)$$

7. Excess carbon in the products from a carbon balance is assumed to be carbon contained in the solid particles and tars in the produce gas, not collected in the cyclone. The carbon balance involves fuel rate, fuel carbon content, char rate, char carbon content, dry gas flowrate and dry gas composition (see Figure A-5). The mass of carbon exiting in the gas as solid particles and tar is calculated as the difference of the incoming carbon in the fuel and the exiting carbon in the char and in the gas as CO, CO_2 and THC (see Equations 10 through 14).

$$\dot{m}_{pc} = \dot{m}_{fc} - \dot{m}_{cc} - \dot{m}_{gc} \qquad (10)$$

$$\dot{m}_{fc} = \dot{m}_f \ W_{fc} \qquad (11)$$

$$\dot{m}_{cc} = \dot{m}_c \ W_{cc} \qquad (12)$$

$$\dot{m}_{gc} = \dot{V}_g \left(\frac{Pr}{Rtr}\right) M_c \left(X_{CO} + X_{CO_2} + X_{CH_4} + 2X_{C_2H_4}\right) \qquad (13)$$

8. The excess mass term represents the mass of the solid particles not collected in the cyclone and the tars in the product gas and is calculated using Equation 14 below. Note that the water vapor in the product gas ($\dot{m}_v$) is obtained from the product gas water vapor mass flowrate determined by the hydrogen balance.

$$\dot{m}_{ex} = \dot{m}_f + \dot{m}_f + \dot{m}_a - \dot{m}_g - \dot{m}_v - \dot{m}_c \qquad (14)$$

Energy Balance Calculations

An energy balance for a steady state process equates the energy entering and exiting a control volume. For a gasifier, the major energy input is the heat of combustion of the fuel and the energy outputs include the heat of combustion and sensible heat of the gas, the sensible heat and heat of combustion of the char, and convection and radiation losses. To compute a consistent energy balance, the reference state of all of the water entering or leaving must be consistent. The reference state of water here has been chosen as liquid at 25 degrees centrigrade. Higher heating values of the fuel and gas are used in the energy balance since these are references to liquid water. The terms used in the energy balance calculations are described in Table A-2. The method used to analyze energy balance data is described below.

1. Energy in the fuel includes the heat of combustion of the dry fuel and the sensible heat of the fuel and the fuel moisture. Since the reference temperature and the temperature of the fuel as it enters the gasifier are approximately equal, the sensible heat of the fuel and fuel moisture are small. The heat of combustion of the fuel is determined by combusting a dry sample of the fuel in a bomb calorimeter. The bomb calorimeter measures the enthalpy at constant volume and approximately constant temperature. This differs from the desired enthalpy for gasification, an approximately constant pressure process, by the flow work of moving reactants into the control volume and removing products from the control volume. This ccorrection is given in Equation 15 and is explained in detail by Jenkins (26).

$$H_f = U_f + \frac{1}{2}\left(Z_f - \frac{Y_f}{2}\right)\frac{RTr}{M_f} \qquad (15)$$

2. The sensible and latent heat of the air blast can be calculated from the temperature and relative humidity of the air. This energy was found by Jenkins (18) to be less than 1% of the heat of combustion of the fuel and has been ignored in the energy balance computations.

3. Gas energy outputs include the heat of combustion and sensible heat of the dry gas and the sensible and latent heat of the water in the gas.
   a. The heat of combustion of the dry gas is calculated by multiplying the volume fracation of each gas species by the higher heating value of the species and summing over all species as in Equation 16. This quantity multiplied by the dry gas rate equals the chemical energy production rate.

$$E_g^H = \sum_{i=1}^{n} E_i^H \, X_i \qquad (16)$$

   b. The sensible heat of the dry gas and the sensible and latent heat of the water vapor in the gas, released upon cooling the gas from the gas exit temperature to the reference temperature,, can be analyzed by considering an energy balance for a condenser system

Table A-2

LIST OF ENERGY BALANCE TERMS

Description of Term	Symbol
Enthalpies	
enthalpy of combustion of fuel at constant pressure (MJ/kg)	H_f
enthalpy of combustion at constant volume (internal energy) of fuel (MJ/kg)	U_f
enthalpy of combustion of char at constant pressure (MJ/kg)	H_c
enthalpy of combustion at constant volume (internal energy) of char (MJ/kg)	U_c
enthalpy of combustion of fly ash at constant pressure (MJ/kg)	H_{fa}
enthalpy of combustion of fly ash at constant volume (internal energy) of fly ash (MJ/kg)	U_{fa}
enthalpy of liquid water at temperature T	H_ℓ^T
enthalpy of water vapor at temperature T	H_v^T
Mole fractions	
kg mole hydrogen in fuel per kg mole fuel	Y_f
kg mole oxygen in fuel per kg mole fuel	Z_f
kg mole hydrogen in char per kg mole char	Y_c
kg mole oxygen in char per kg mole char	Z_c
kg mole hydrogen in fly ash per kg mole fly ash	Y_{fa}
kg mole oxygen in fly ash per kg mole fly ash	Z_{fa}
Gas heating values	
higher heating value of product gas mixture (MJ/m^3)	E_g^H
higher heating value of species i (MJ/m^3)	E_i^H
lower heating value of product gas (MJ/m^3)	E_g^L
lower heating value of species i (MJ/m^3)	E_i^L

Table A-2

Description of Term	Symbol
Sensible heat	
sensible heat of gas component i between temperatures T_1 and T_2 (MJ/kg)	$\Delta H_i \, {}^{T_1}_{T_2}$
sensible heat of dry gas mixture between temperatures T_1 and T_2 (MJ/kg)	$\Delta H_g \, {}^{T_1}_{T_2}$
Efficiency	
hot gas efficiency	n_{HG}
cold gas efficiency	n_{CG}
Other	
saturation vapor pressure at temperature T	P_v^T
heat removed by cooling wet gas (MJ/hr)	q_c
heat losses due to radiation, convection, and unaccounted quantities (MJ/hr)	q_L

(Figure A-6). The energy entering the condenser is the enthalpy of the hot dry gas and the enthalpy of the hot water vapor. The energy leaving the condenser includes the enthalpy of the cool dry gas, the enthalpy of the cool water vapor, the enthalpy of the condensed water, and energy released into the environment. This energy balance is expressed in Equation 17.

$$q_c = \dot{m}_g \; \Delta \; H_{g_{Tr}}^{Te} + (W_{gv}^{Te} \, H_v^{Te} - W_{gv}^{Tr} \, H_v^{Tr}) - (W_{gv}^{Te} - W_{gv}^{Tr}) \, H_{\ell}^{Tr} \qquad (17)$$

The change in enthalpy of the dry gas between the gas exit temperature and the reference temperature is calculated from the sensible heat and volume fractions of each gas species present (see Equation 18). The sensible heat of each gas species is determined by subtracting the enthalpy of the gas species at the gas exit temperature from the enthalpy at the reference temperature. The enthalpies are determined using the JANAF thermochemical tables (16).

$$\Delta \, H_{g_{Tr}}^{Te} = \sum_{i=1}^{n} \Delta \; H_{i_{Tr}}^{Te} \, X_i \qquad (18)$$

The enthalpy of the hot vapor is a function of the specific humidity of the hot gas which can be calculated from experimental moisture content measurement. The enthalpy of the cool vapor depends on the specific humidity of the gas leaving the condenser which is assumed to be saturated. The specific humidity of saturated water vapor is calculated from the saturated vapor pressure at the reference temperature and the molecular weight of the gas mixture by Equation 19. The saturated vapor pressure was obtained from tables compiled by Reynolds (31).

$$W^{Tr} = \frac{P_v^{Tr}}{Pr - P_v^{Tr}} \left(\frac{M_{H_2O}}{M_g} \right) \qquad (19)$$

4. The char removed from the gasifier represents another energy output. The heat of combustion of the char is determined by bomb calorimeter measurements and is corrected in the same manner as for the fuel (see Equation 20).

$$H_C = U_C + \frac{1}{2} \left(Z_C - \frac{Y_C}{2} \right) \frac{RTr}{M_C} \qquad (20)$$

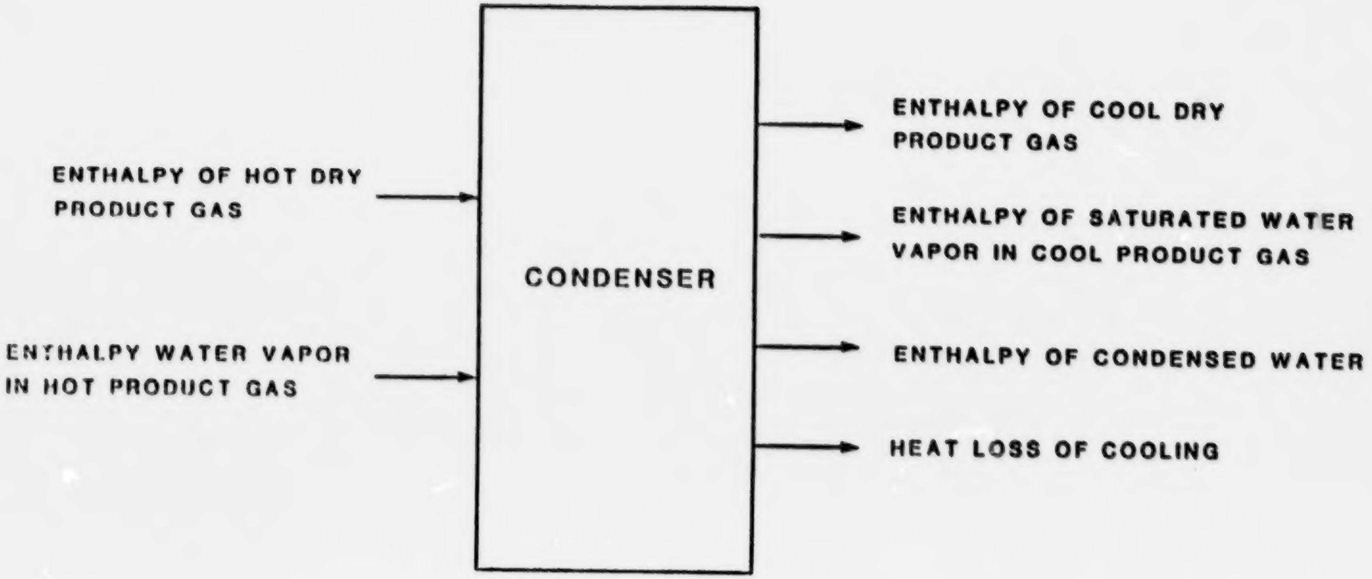
ENTHALPY OF HOT DRY PRODUCT GAS
ENTHALPY WATER VAPOR IN HOT PRODUCT GAS
CONDENSER
ENTHALPY OF COOL DRY PRODUCT GAS
ENTHALPY OF SATURATED WATER VAPOR IN COOL PRODUCT GAS
ENTHALPY OF CONDENSED WATER
HEAT LOSS OF COOLING

Figure A-6. Condenser energy balance.

5. The fly ash collected by the cyclone represents an energy output. The heat of combustion of the fly ash is determined by bomb calorimeter measurements and is corrected in the same manner as for the fuel and char (see Equation 21)

$$H_{fa} = U_{fa} + \frac{1}{2} \left(Z_{fa} - \frac{Y_{fa}}{2}\right) \frac{Rtr}{M_{fa}} \tag{21}$$

6. Energy losses are determined by difference of the energy inputs and outputs (see Equation 22). Energy is lost to the environment by convection and radiation. The calculated losses are also a product of measurement errors and unaccounted for quantities including the heat of combustion of the particulate matter and tars in the gas, and the sensible heat of the char, particulate matter and tars.

$$q_L = \dot{m}_f H_f - \dot{m}_c H_c - \dot{m}_{fa} H_{fa} - \dot{V}_g E_g^H - q_c \tag{22}$$

Process Efficiency

Efficiency is defined here as the ratio of the energy in the gas products to the heating value of the fuel. The energy in the gas is partly a function of the temperature of the gas because sensible energy increases with temperature. Therefore, the efficiency of a gasifier supplying hot gas to a burner is higher than for supplying an internal combustion engine where the gas must be cooled before induction. For both burners and engines, the water produced for combusting the hydrogen and hydrocarbon gases leaves in the vapor phase. The heat of vaporization is not available to the process and so the lower heating value of the product gas is used (see Equation 23). Hot and cold gas efficiencies have been calculated by Equations 24 and 25. Hot gas efficiency is applicable to operations where the sensible heat of the gas is utilized, such as in a burner. For operations where the gas must be cooled to be utilized, such as in an internal combustion engine, the sensible heat is not used and the cold gas efficiency is appropriate.

$$E_g^L = \sum_{i=1}^{n} E_i^L X_i \tag{23}$$

$$\eta_{HG} = \frac{\dot{V}_g E_g^L + q_c}{\dot{m}_f \quad H_f} \tag{24}$$

$$\eta_{CG} = \frac{\dot{V}_g \; E_g^L}{\dot{m}_f \quad H_f} \tag{25}$$

APPENDIX B

COMPUTER PROGRAM LISTING AND OUTPUT DATE FOR THE MASS AND ENERGY BALANCES

```
C     ENERGY BALANCE FOR GASIFIER
C     LAST REVISION 14-APR-83   WRITTEN BY G. LAMOREY
C     ************************************************************
      DIMENSION FU(3),FA(3),CH(3),X(7),MW(7),JAN(161),HHVT(7),LHVT(7)
      BYTE SPEC(30),TITLE(80),DATAF(10),DATOU(10)
      REAL NA,NDG,NAC,MG,MD,MW,CHECK,JAN,PARTG,LHV,LHVB,LHVT,LO
      DATA SPEC /'C','O',' ','C','O','2','C','H','4',
      1'C','2','H','H','2',' ','N','2',' ','O','2',' ',
      1'C',' ',' ','H',' ',' ','O',' ',' '/
      DATA MW /28.011,44.011,16.043,28.054,2.016,
      1 28.164,32.0/
      DATA JAN /
      1 0.013,0.711,1.417,2.137,2.873,3.627,4.397,5.183,
      1 5.983,6.794,7.616,8.446,9.285,10.130,10.980,11.836,
      1 12.697,13.561,14.430,15.301,16.175,17.052,17.931,
      1 0.016,0.958,1.987,3.087,4.245,5.453,6.702,7.984,
      1 9.296,10.632,11.988,13.362,14.750,16.152,17.565,
      1 18.987,20.418,21.857,23.303,24.755,26.212,27.674,
      1 29.141,
      1 0.016,0.923,1.960,3.138,4.454,5.897,7.458,9.125
      1 10.887,12.732,14.652,16.637,18.679,20.772,22.910
      1 25.086,27.298,29.540,31.809,34.103,36.418,38.753,
      1 41.106,
      1 0.019,1.167,2.55,4.143,5.918,7.851,9.92,12.109,
      1 14.404,16.791,19.258,21.797,24.397,27.051,29.753,
      1 32.498,35.279,38.094,40.937,43.807,46.7,49.614,
      1 52.546,
      1 0.013,0.707,1.406,2.106,2.808,3.514,4.226,
      1 4.944,5.67,6.404,7.148,7.902,8.668,9.446,10.233,
      1 11.030,11.836,12.651,13.475,14.307,15.146,15.993,
      1 16.848,
      1 0.013,0.71,1.413,2.125,2.853,3.596,4.355,5.129,
      1 5.917,6.718,7.529,8.35,9.179,10.015,10.858,11.707,
      1 12.56,13.418,14.28,15.146,16.015,16.886,17.761,
      1 0.013,0.724,1.455,2.210,2.988,3.786,4.60,
      1 5.427,6.266,7.114,7.971,8.835,9.706,10.583,11.465,
      1 12.354,13.249,14.149,15.054,15.966,16.882,17.804,
      1 18.732/
      DATA HHVT /67.637,0.0,212.8,337.23,68.317,0.0,0.0/
      DATA LHVT /67.637,0.0,191.76,316.24,57.798,0.0,0.0/
C     *****************************************************************
190   TYPE *,' ENTER TITLE OF INPUT DATA FILE AS NAME.DAT'
      READ(5,10)NNCH,(DATAF(I),I=1,NNCH)
      WRITE(5,11)(DATAF(I),I=1,NNCH)
      TYPE *,' ENTER TITLE OF OUTPUT FILE AS NAME.DAT'
      READ(5,10)NNCH,(DATOU(I),I=1,NNCH)
      WRITE(5,11)(DATOU(I),I=1,NNCH)
      OPEN(UNIT=2,TYPE='OLD',NAME=DATAF)
      READ(2,10)NCH,(TITLE(I),I=1,NCH)
      READ(2,150)TEMPF
      READ(2,150)CSVP
      READ(2,150)AIRV
      READ(2,150)WFR
      DO 160 I=1,3
            READ(2,150)FU(I)
```

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```
160            FU(I)=FU(I)/100
      READ(2,150)FMC
      READ(2,150)ENTF
      DO 170 I=1,7
               READ(2,150)X(I)
170            X(I)=X(I)/100
      READ(2,150)CFR
      READ(2,150)TEMPG
      READ(2,150)EH1
      READ(2,150)CHR
      DO 220 I=1,3
               READ(2,150)CH(I)
220            CH(I)=CH(I)/100
      READ(2,150)CE
      READ(2,150)FAR
      DO 210 I=1,3
               READ(2,150)FA(I)
210            FA(I)=FA(I)/100
      READ(2,150)FAE
150   FORMAT(28X,F8.3)
      CLOSE(UNIT=2)
C     ************************************************************
C     DATA PROCESSING STARTS HERE. LOWG AND PARTG ARE USED FOR INTERPOLATION
      LOWG=INT(TEMPG/100)      !OF JANAF TABLES  LOWG CONTAINS GAS TEMP
      PARTG=TEMPG-LOWG*100     !TRUNCATED TO HUNDREDS, PARTG CONTAINS TENS
      ENTG=0                   !AND ONES PLACE DIGITS OF GAS TEMP.
      HHV=0                    !ENTG IS GAS ENTHALPY, HHV IS GAS HIGHER
      LHV=0                    !HEATING VALUE, LHV IS GAS LOWER HEATING
      MD=0                     !VALUE, MD IS MOLECULAR WEIGHT OF DRY GAS,
      MWW=0                    !MWW IS MOLECULAR WEIGHT OF WET GAS.
      DO 135 I=0,6
            ENTG=ENTG+(PARTG*(JAN(LOWG-1+(I*23))-JAN(LOWG-2+(I*23)))/100+
      1     JAN(LOWG-2+(I*23)))*X(I+1)      !IN KCAL/G MOLE.
            HHV=HHV+HHVT(I+1)*X(I+1)        !IN KCAL/G MOLE.
            LHV=LHV+LHVT(I+1)*X(I+1)        !IN KCAL/G MOLE.
135         MD=MD+X(I+1)*MW(I+1)
      ENTG=ENTG*4.1855/MD                   !IN MJ/KG.
      DD=MD/(0.08206*TEMPF)    !DRY GAS DENSITY IN KG/M3.
      HHV=HHV*DD*4.1855/MD                  !IN MJ/M3.
      LHV=LHV*DD*4.1855/MD                  !IN MJ/M3.
      HHVB=HHV*26.839                       !IN BTU/FT3.
      LHVB=LHV*26.839                       !IN BTU/FT3.
C     ******************************************************************
      FUT=FU(1)+FU(2)+FU(3)    !CALCULATION OF CONSTANT PRESSURE
      FCC=FUT*.72/FU(1)        !FUEL ENTHAPLY, ENTFP, REQUIRES CALCULATION
      FUH=FU(2)*100*FCC/FUT    !OF H AND O COEFFICIENTS, FUH AND FUO,
      FUO=FU(3)*6.25*FCC/FUT   !AND FUEL MOLECULAR WEIGHT FMW BASED
      FMW=72+FUH+16*FUO        !ON 6 MCLES C.
      ENTFP=ENTF+1.239*(FUO-FUH/2)/FMW
      FMCF=FMC/100             !CONVERT PERCENT MOISTURE TO FRACTION.
      DRF=WFR*(1-FMCF)         !DRF IS DRY FUEL RATE.
      WFMC=WFR*FMCF            !WFMC IS FUEL MOISTURE MASS FLOWRATE.
      AIRM=AIRV*21170/TEMPF    !AIRM IS AIR MASS FLOWRATE.
      AFR=AIRM/WFR             !AFR IS THE AIR FUEL RATIO.
      DGFV=.79*AIRV/X(6)       !DGFV IS DRY GAS VOLUME FLOWRATE.
      DGFM=DGFV*731.0*MD/TEMPF!DGFM IS DRY GAS MASS FLOWRATE.
      AQP=18.016*CSVP/(MD*(1013.3-CSVP))+ !AQP IS KG H20/KG DRY GAS
      1 CFR/(DD*1000) !FROM H20 IN SAT GAS AND MASS OF CONDENSATE.
      AQM=AQP*DGFM            !AQM IS THE MASS FLOWRATE OF H20 IN GAS.
      CF=FU(1)*DRF                    !CF IS C IN FUEL.
      CFA=FAR*FA(1)                   !CFA IS C IN FLY ASH.
      CCH=CHR*CH(1)                   !CCH IS C IN CHAR.
      CDG=DGFV*8772.*(X(1)+X(2)+X(3)+2*X(4))/TEMPF !CDG IS C IN DRY GAS.
      NA=AIRV*16265./TEMPF            !NA IS N IN AIR.
      NDG=DGFV*20585.*X(6)/TEMPF      !NDG IS N IN DRY GAS.
      OA=AIRV*4912./TEMPF             !OA IS O IN AIR.
      OFMC=FMCF*DRF*.889              !OFMC IS O IN FUEL MOISTURE.
      OF=FU(3)*DRF                    !OF IS O IN DRY FUEL.
      OAQM=AQM*.889                   !OAQM IS O IN H20 IN GAS.
      ODG=DGFV*11695.*(X(1)+2*X(2))/TEMPF     !ODG IS O IN DRY GAS.
      OCH=CHR*CH(3)                   !OCH IS O IN CHAR.
      OFA=FAR*FA(3)                   !OFA IS O IN FLY ASH.
      HF=FU(2)*DRF                    !HF IS H IN DRY FUEL.
      HFMC=FMCF*DRF*.111              !HFMC IS H IN FUEL MOISTURE.
      HAQM=AQM*.111                   !HAQM IS H IN H20 IN GAS.
      HDG=DGFV*730.9*(4*X(3)+4*X(4)+2*X(5))/TEMPF     !HDG ID H IN DRY GAS.
      HCH=CHR*CH(2)                   !HCH IS H IN CHAR.
      HFA=FAR*FA(2)                   !HFA IS H IN FLY ASH.
      EXC=100*(CF-CCH-CFA-CDG)/CF     !EXC IS CARBON CLOSURE.
      EXH=100*(HF+HFMC-HDG-HAQM-HCH-HFA)/(HF+HFMC) !EXH IS HYDROGEN CLOSURE.
      EXO=100*(OA+OF+OFMC-ODG-OAQM-OCH-OFA)   !EXO IS OXYGEN CLOSURE.
      1 /(OA+OF+OFMC)
      EXN=100*(NA-NDG)/NA
      EXM=100*(WFR+AIRM-DGFM-AQM-CHR-FAR)     !EXM IS OVERALL CLOSURE.
      1 /(WFR+AIRM)
      W2=(0.03226)*18.02/MD           !W2 IS KG H20/KG DRY GAS AT T2.
      QC=DGFM*(ENTG+(AQP*EH1-W2*2.546) !QC IS HEAT REMOVED BY COOLING
      1 -((AQP-W2)*1.033))    !GAS FROM GAS EXIT TEMPERATURE TO 298K.
      EGH=DGFV*HHV*60 !ECH IS CHEMICAL ENERGY OF GAS IN MJ/HR USING HHV.
      EGL=DGFV*LHV*60 !ECL IS CHEMICAL ENERGY OF GAS IN MJ/HR USING LHV.
C     ********************************************************************
      IF (FU(2)-(FU(3)/8).LE.0) BW=FU(2)*9    !BW IS BOUND WATER %, WITH
      IF (FU(2)-(FU(3)/8).GT.0) BW=FU(3)*1.125!H IN EXCESS OR LIMITING.
      EFL=WFR*BW*(1-FMCF)*2.257       !EFL IS LATENT HEAT IN BOUND WATER.
      EFM=WFR*FMCF*2.257      !EFM IS LATENT HEAT OF FUEL MOISTURE CONTENT.
      EFG=WFR*(1-FMCF)*ENTFP  !BFG IS GROSS ENERGY IN DRY FUEL(MJ/HR).
      EFN=EFG-EFL-EFM         !EFN IS NET ENERGY IN DRY FUEL(MJ/HR).
      ECH=CE*CHR              !ECH IS ENERGY IN CHAR(MJ/HR).
      EFA=FAE*FAR             !EFA IS ENERGY IN FLY ASH(MJ/HR).
      LO=EFG-EGH-QC-ECH-EFA   !LO IS ENERGY LOSSES(MJ/HR).
      PC=(EGH/EFG)*100        !PC IS CHEMICAL ENERGY IN GAS(%).
      PS=(QC/EFG)*100         !PS IS SENSIBLE ENERGY IN GAS(%).
      PCH=(ECH/EFG)*100       !PCH IS ENERGY OUT IN CHAR(%).
      PFA=(EFA/EFG)*100       !PFA IS ENERGY OUT IN FLY ASH(%).
      PL=(LO/EFG)*100         !PL IS ENERGY LOSSES(%).
      HGO=EGL+QC              !XX IS HOT GAS OUTPUT(MJ/HR).
      HG=(HGO/EFG)*100        !HG IS HOT GAS EFFICIENCY.
      CG=(EGL/EFG)*100        !CG IS COLD GAS EFFICIENCY.
      AA=11.53*FU(1)+34.34*   !AA IS STOICH AIR KG AIR/KG DRY FUEL.
      1  (FU(2)-(FU(3)/8))
      AS=AA*WFR*(1-FMCF)*TEMPF*4.7225E-5      !AS IS STOICH AIR M3/MIN.
      AR=(AIRV/AS)*100                      !AR IS GASIFICATION AIR/STOICH AIR.
C***********************************************************************
C     OUTPUT TO DISKFILE.
      OPEN(UNIT=2,TYPE='NEW',NAME=DATOU)
      WRITE(2,22)(TITLE(I),I=1,NCH)
      WRITE(2,25)
      WRITE(2,38)TEMPF
      WRITE(2,32)CSVP
      WRITE(2,37)AIRV
      WRITE(2,39)
      DO 400 I=8,10
400         WRITE(2,20)SPEC(I*3-2),FU(I-7)*100,CH(I-7)*100,FA(I-7)*100
      WRITE(2,21)ENTF,CE,FAE
      WRITE(2,28)WFR,CHR,FAR
      WRITE(2,30)FMC
      WRITE(2,41)
      DO 450 I=1,7
450         WRITE(2,12)SPEC(I*3-2),SPEC(I*3-1),SPEC(I*3),X(I)*100
      WRITE(2,33)CFR
      WRITE(2,140)TEMPG
      WRITE(2,290)EH1
      WRITE(2,23)
      WRITE(2,26)
      WRITE(2,350)OA,NA,AIRM
      WRITE(2,352)CF,HF,OF,DRF
      WRITE(2,353)HFMC,OFMC,WFMC
      WRITE(2,355)CDG,HDG,ODG,NDG,DGFM
      WRITE(2,357)HAQM,OAQM,AQM
      WRITE(2,358)CCH,HCH,OCH,CHR
      WRITE(2,359)CFA,HFA,OFA,FAR
      WRITE(2,465)EXC,EXH,EXO,EXN,EXM
      WRITE(2,330)DGFV
      WRITE(2,50)MD
      WRITE(2,55)DD
      WRITE(2,360)AQP*100
      WRITE(2,125)AA
      WRITE(2,126)AS,AR
      WRITE(2,130)AFR
      WRITE(2,27)
      WRITE(2,40)HHV,HHVB
      WRITE(2,45)LHV,LHVB
      WRITE(2,75)EFG
      WRITE(2,77)EFN
      WRITE(2,80)ECH,PCH
      WRITE(2,82)EFA,PFA
      WRITE(2,95)QC,PS
      WRITE(2,105)EGH,PC
      WRITE(2,110)LO,PL
      WRITE(2,122)HG
      WRITE(2,123)CG
      DO 460 I=1,10
460         WRITE(2,24)
      CLOSE(UNIT=2)
      TYPE *,' ENTER 0 TO STOP, 1 TO CONTINUE.'
      READ(5,*)J
      IF (J.EQ.1) GO TO 190
10    FORMAT(Q,50A1)
11    FORMAT(' ',10A)
38    FORMAT(' TEMPERATURE FOR FLOW RATES          ',F7.2,' K')
32    FORMAT(' SAT VAPOR PRESSURE AT THIS T        ',F7.2,' MILLIBARS')
37    FORMAT(' AIR VOLUME FLOW RATE                ',F7.2,' M3/MIN')
20    FORMAT('                           ',1A,'      ',3(F7.3,2X))
30    FORMAT(' FUEL MOISTURE CONTENT               ',F7.2,' % DRY BASIS')
12    FORMAT('                               ',3A,'   ',F7.2)
33    FORMAT(' CONDENSER WATER PRODUCTION RATE ',F7.3,' G/M3 DRY GAS')
140   FORMAT(' GAS TEMPERATURE                     ',F7.2,' K')
290   FORMAT(' HOT GAS SAT VAPOR ENTHALPY           ',F7.3,' MJ/KG')
21    FORMAT(' ENTHALPY HHV(MJ/KG)             ',3(F7.3,2X))
28    FORMAT(' MASS FLOWRATE(WET KG/HR)        ',3(F7.3,2X))
22    FORMAT(' ',50A1)
23    FORMAT(' OUTPUT DATA:')
24    FORMAT(' ')
25    FORMAT(' INPUT DATA:')
26    FORMAT(' MASS BALANCE(KG/HR):  C       H       O',
     1 '       N     OVERALL')
27    FORMAT(' ENERGY BALANCE:')
39    FORMAT(' COMPOSITION(% DRY WT):         FUEL      CHAR    FLY ASH')
41    FORMAT(' DRY GAS COMPOSITION (% VOL):')
330   FORMAT(' DRY GAS VOLUME FLOWRATE             ',F7.2,' M3/MIN')
360   FORMAT(' GAS WATER VAPOR MASS FRACTION  ',F7.2,
     1 ' % DRY BASIS')
350   FORMAT('   AIR               ',16X,3F8.2)
352   FORMAT('   DRY FUEL          ',3F8.2,8X,F8.2)
353   FORMAT('   FUEL MOISTURE  ',8X,2F8.2,8X,F8.2)
355   FORMAT('   DRY GAS           ',5F8.2)
357   FORMAT('   GAS MOISTURE   ',8X,2F8.2,8X,F8.2)
358   FORMAT('   CHAR              ',3F8.2,8X,F8.2)
359     FORMAT('   FLY ASH           ',3F8.2,8X,F8.2)
465   FORMAT('   CLOSURE(%)      ',5F8.2)
40    FORMAT(' GAS HHV AT 298 K                     ',F7.3,' MJ/M3    ',
     1 F7.2,' BTU/FT3')
45    FORMAT(' GAS LHV AT 298 K                     ',F7.3,' MJ/M3    ',
     1 F7.2,' BTU/FT3')
50    FORMAT(' MOLEC. WT.-DRY GAS                   ',F7.3)
55    FORMAT(' DENSITY- DRY GAS                     ',F7.3,' KG/M3')
75    FORMAT(' DRY FUEL ENERGY-HHV                 ',F7.2,' MJ/HR')
77    FORMAT('                  LHV                ',F7.2,' MJ/HR')
80    FORMAT(' ENERGY IN CHAR                      ',F7.2,' MJ/HR     ',
     1 F7.2,' %')
82    FORMAT(' ENERGY IN FLY ASH                   ',F7.2,' MJ/HR     ',
     1 F7.2,' %')
95    FORMAT(' SENSIBLE ENERGY IN GAS              ',F7.2,' MJ/HR     ',
     1 F7.2,' %')
105   FORMAT(' CHEMICAL ENERGY IN GAS              ',F7.2,' MJ/HR     ',
     1 F7.2,' %')
110   FORMAT(' ENERGY LOSSES                       ',F7.2,' MJ/HR     ',
     1 F7.2,' %')
122   FORMAT(' EFFICIENCY                  HOT GAS ',F7.2,' %')
123   FORMAT('                            COLD GAS ',F7.2,' %')
```

```
130   FORMAT(' AIR/FUEL RATIO                 ',F7.2)
126   FORMAT('                   VOLUME BASIS ',F7.2,' M3/MIN    ',
     1 F7.2,' %')
125   FORMAT(' STOICH AIR          MASS BASIS ',F7.2,' KG/KG FUEL')
      END
```

```
C.E. GASIFIER RUN 36
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.00 K
SAT VAPOR PRESSURE AT THIS T     23.62 MILLIBARS
AIR VOLUME FLOW RATE              1.94 M3/MIN
COMPOSITION(% DRY WT):         FUEL      CHAR    FLY ASH
                     C       47.540    53.100    61.580
                     H        5.740     0.550     0.550
                     O       41.690     0.480     0.650
ENTHALPY HHV(MJ/KG)          18.710    18.970    21.020
MASS FLOWRATE(WET KG/HR)     93.000    13.500     0.470
FUEL MOISTURE CONTENT             8.60 % DRY BASIS
DRY GAS COMPOSITION (% VOL):
                       CO      20.56
                       CO2     13.83
                       CH4      5.38
                       C2H      2.31
                       H2      15.44
                       N2      42.48
                       O2       0.00
CONDENSER WATER PRODUCTION RATE 136.908 G/M3 DRY GAS
GAS TEMPERATURE                 855.00 K
HOT GAS SAT VAPOR ENTHALPY        3.664 MJ/KG
OUTPUT DATA:
MASS BALANCE(KG/HR):  C       H       O       N     OVERALL
  AIR                                32.49  107.58  140.03
  DRY FUEL          40.41    4.88    35.44           85.00
  FUEL MOISTURE              0.81     6.50            8.00
  DRY GAS           47.90    5.54    69.37  107.56  230.48
  GAS MOISTURE               3.71    29.75           33.47
  CHAR               7.17    0.07     0.06           13.50
  FLY ASH            0.29    0.00     0.00            0.47
  CLOSURE(%)       -36.98  -64.01   -33.27    0.02  -19.26
DRY GAS VOLUME FLOWRATE           3.60 M3/MIN
MOLEC. WT.-DRY GAS               25.632
DENSITY- DRY GAS                  1.066 KG/M3
GAS WATER VAPOR MASS FRACTION    14.52 % DRY BASIS
STOICH AIR           MASS BASIS   5.66 KG/KG FUEL
                   VOLUME BASIS   6.66 M3/MIN       29.10 %
AIR/FUEL RATIO                    1.51
ENERGY BALANCE:
GAS HHV AT 298 K                  7.606 MJ/M3     204.14 BTU/FT3
GAS LHV AT 298 K                  7.042 MJ/M3     189.00 BTU/FT3
DRY FUEL ENERGY-HHV            1590.09 MJ/HR
                LHV            1482.06 MJ/HR
ENERGY IN CHAR                  256.10 MJ/HR        16.11 %
ENERGY IN FLY ASH                 9.88 MJ/HR         0.62 %
SENSIBLE ENERGY IN GAS          251.79 MJ/HR        15.83 %
CHEMICAL ENERGY IN GAS         1644.78 MJ/HR       103.44 %
ENERGY LOSSES                  -572.45 MJ/HR       -36.00 %
EFFICIENCY              HOT GAS 111.60 %
                       COLD GAS  95.77 %
```

```
C.E. GASIFIER RUN 36X
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.00 K
SAT VAPOR PRESSURE AT THIS T     23.62 MILLIBARS
AIR VOLUME FLOW RATE              1.94 M3/MIN
COMPOSITION(% DRY WT):        FUEL     CHAR    FLY ASH
                      C      47.540   53.100   61.580
                      H       5.740    0.550    0.550
                      O      41.690    0.480    0.650
ENTHALPY HHV(MJ/KG)          18.710   18.970   21.020
MASS FLOWRATE(WET KG/HR)    105.300   13.500    0.470
FUEL MOISTURE CONTENT             8.60 % DRY BASIS
DRY GAS COMPOSITION (% VOL):
                         CO       20.56
                         CO2      13.83
                         CH4       5.38
                         C2H       2.31
                         H2       15.44
                         N2       42.48
                         O2        0.00
CONDENSER WATER PRODUCTION RATE 136.908 G/M3 DRY GAS
GAS TEMPERATURE                 855.00 K
HOT GAS SAT VAPOR ENTHALPY        3.664 MJ/KG
OUTPUT DATA:
MASS BALANCE(KG/HR):  C       H       O       N      OVERALL
  AIR                               32.49  107.58  140.03
  DRY FUEL          45.75    5.52   40.12           96.24
  FUEL MOISTURE              0.92    7.36            9.06
  DRY GAS           47.90    5.54   69.37  107.56  230.48
  GAS MOISTURE               3.71   29.75           33.47
  CHAR               7.17    0.07    0.06           13.50
  FLY ASH            0.29    0.00    0.00            0.47
  CLOSURE(%)       -20.98  -44.85  -24.03    0.02  -13.28
DRY GAS VOLUME FLOWRATE           3.60 M3/MIN
MOLEC. WT.-DRY GAS               25.632
DENSITY- DRY GAS                  1.066 KG/M3
GAS WATER VAPOR MASS FRACTION    14.52 % DRY BASIS
STOICH AIR          MASS BASIS    5.66 KG/KG FUEL
                  VOLUME BASIS    7.54 M3/MIN      25.70 %
AIR/FUEL RATIO                    1.33
ENERGY BALANCE:
GAS HHV AT 298 K                  7.606 MJ/M3     204.14 BTU/FT3
GAS LHV AT 298 K                  7.042 MJ/M3     189.00 BTU/FT3
DRY FUEL ENERGY-HHV            1800.40 MJ/HR
                LHV            1678.08 MJ/HR
ENERGY IN CHAR                  256.10 MJ/HR       14.22 %
ENERGY IN FLY ASH                 9.88 MJ/HR        0.55 %
SENSIBLE ENERGY IN GAS          251.79 MJ/HR       13.99 %
CHEMICAL ENERGY IN GAS         1644.78 MJ/HR       91.36 %
ENERGY LOSSES                  -362.15 MJ/HR      -20.11 %
EFFICIENCY             HOT GAS   98.57 %
                      COLD GAS   84.58 %
```

```
C.E. GASIFIER RUN 37
INPUT DATA:
TEMPERATURE FOR FLOW RATES        293.00 K
SAT VAPOR PRESSURE AT THIS T       23.62 MILLIBARS
AIR VOLUME FLOW RATE                1.96 M3/MIN
COMPOSITION(% DRY WT):          FUEL      CHAR    FLY ASH
                      C       45.170    46.760    57.940
                      H        5.660     0.480     0.820
                      O       42.810     0.690     1.130
ENTHALPY HHV(MJ/KG)           18.520    14.740    19.990
MASS FLOWRATE(WET KG/HR)      86.800    13.800     0.680
FUEL MOISTURE CONTENT              12.40 % DRY BASIS
DRY GAS COMPOSITION (% VOL):
                         CO        19.89
                         CO2       13.78
                         CH4        3.68
                         C2H        1.58
                         H2        15.36
                         N2        45.71
                         O2         0.00
CONDENSER WATER PRODUCTION RATE 143.628 G/M3 DRY GAS
GAS TEMPERATURE                   864.00 K
HOT GAS SAT VAPOR ENTHALPY          3.684 MJ/KG
OUTPUT DATA:
MASS BALANCE(KG/HR):  C        H        O        N      OVERALL
  AIR                                 32.86   108.80   141.62
  DRY FUEL          34.35     4.30    32.55             76.04
  FUEL MOISTURE               1.05     8.38             10.76
  DRY GAS           41.08     4.37    64.16   108.78   218.49
  GAS MOISTURE                3.64    29.18             32.82
  CHAR               6.45     0.07     0.10             13.80
  FLY ASH            0.39     0.01     0.01              0.68
  CLOSURE(%)       -39.55   -51.18   -26.62     0.02   -16.36
DRY GAS VOLUME FLOWRATE             3.39 M3/MIN
MOLEC. WT.-DRY GAS                 25.853
DENSITY- DRY GAS                    1.075 KG/M3
GAS WATER VAPOR MASS FRACTION      15.02 % DRY BASIS
STOICH AIR           MASS BASIS     5.31 KG/KG FUEL
                   VOLUME BASIS     5.59 M3/MIN       35.06 %
AIR/FUEL RATIO                      1.63
ENERGY BALANCE:
GAS HHV AT 298 K                    6.459 MJ/M3     173.36 BTU/FT3
GAS LHV AT 298 K                    5.986 MJ/M3     160.65 BTU/FT3
DRY FUEL ENERGY-HHV              1408.05 MJ/HR
                LHV              1301.10 MJ/HR
ENERGY IN CHAR                    203.41 MJ/HR        14.45 %
ENERGY IN FLY ASH                  13.59 MJ/HR         0.97 %
SENSIBLE ENERGY IN GAS            240.70 MJ/HR        17.09 %
CHEMICAL ENERGY IN GAS           1312.84 MJ/HR        93.24 %
ENERGY LOSSES                    -362.50 MJ/HR       -25.75 %
EFFICIENCY              HOT GAS  103.49 %
                       COLD GAS   86.40 %
```

```
C.E. GASIFIER RUN 37X
INPUT DATA:
TEMPERATURE FOR FLOW RATES       293.00 K
SAT VAPOR PRESSURE AT THIS T      23.62 MILLIBARS
AIR VOLUME FLOW RATE               1.96 M3/MIN
COMPOSITION(% DRY WT):          FUEL      CHAR     FLY ASH
                       C       45.170    46.760    57.940
                       H        5.660     0.480     0.820
                       O       42.810     0.690     1.130
ENTHALPY HHV(MJ/KG)            18.520    14.740    19.990
MASS FLOWRATE(WET KG/HR)       96.600    13.800     0.680
FUEL MOISTURE CONTENT             12.40 % DRY BASIS
DRY GAS COMPOSITION (% VOL):
                         CO       19.89
                         CO2      13.78
                         CH4       3.68
                         C2H       1.58
                         H2       15.36
                         N2       45.71
                         O2        0.00
CONDENSER WATER PRODUCTION RATE 143.628 G/M3 DRY GAS
GAS TEMPERATURE                 864.00 K
HOT GAS SAT VAPOR ENTHALPY        3.684 MJ/KG
OUTPUT DATA:
MASS BALANCE(KG/HR):  C        H         O        N      OVERALL
  AIR                                  32.86   108.80   141.62
  DRY FUEL          38.22     4.79     36.23             84.62
  FUEL MOISTURE               1.16      9.33             11.98
  DRY GAS           41.08     4.37     64.16   108.78   218.49
  GAS MOISTURE                3.64     29.18             32.82
  CHAR               6.45     0.07      0.10             13.80
  FLY ASH            0.39     0.01      0.01              0.68
  CLOSURE(%)       -25.39   -35.84    -19.16     0.02   -11.58
DRY GAS VOLUME FLOWRATE           3.39 M3/MIN
MOLEC. WT.-DRY GAS               25.853
DENSITY- DRY GAS                  1.075 KG/M3
GAS WATER VAPOR MASS FRACTION    15.02 % DRY BASIS
STOICH AIR           MASS BASIS   5.31 KG/KG FUEL
                   VOLUME BASIS   6.22 M3/MIN        31.50 %
AIR/FUEL RATIO                    1.47
ENERGY BALANCE:
GAS HHV AT 298 K                  6.459 MJ/M3      173.36 BTU/FT3
GAS LHV AT 298 K                  5.986 MJ/M3      160.65 BTU/FT3
DRY FUEL ENERGY-HHV            1567.02 MJ/HR
                LHV            1448.00 MJ/HR
ENERGY IN CHAR                  203.41 MJ/HR        12.98 %
ENERGY IN FLY ASH                13.59 MJ/HR         0.87 %
SENSIBLE ENERGY IN GAS          240.70 MJ/HR        15.36 %
CHEMICAL ENERGY IN GAS         1312.84 MJ/HR        83.78 %
ENERGY LOSSES                  -203.53 MJ/HR       -12.99 %
EFFICIENCY              HOT GAS  93.00 %
                       COLD GAS  77.63 %
```

```
C.E. GASIFIER RUN 38
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.00 K
SAT VAPOR PRESSURE AT THIS T     23.62 MILLIBARS
AIR VOLUME FLOW RATE              1.95 M3/MIN
COMPOSITION(% DRY WT):         FUEL     CHAR    FLY ASH
                      C      44.310   47.000   52.650
                      H       5.600    0.500    0.730
                      O      39.700    0.050    1.210
ENTHALPY HHV(MJ/KG)          17.120   15.220   18.420
MASS FLOWRATE(WET KG/HR)    100.700   14.300    0.800
FUEL MOISTURE CONTENT             9.70 % DRY BASIS
DRY GAS COMPOSITION (% VOL):
                         CO      17.93
                         CO2     13.16
                         CH4      2.21
                         C2H      0.95
                         H2      14.52
                         N2      51.23
                         O2       0.00
CONDENSER WATER PRODUCTION RATE 144.826 G/M3 DRY GAS
GAS TEMPERATURE                 883.00 K
HOT GAS SAT VAPOR ENTHALPY        3.726 MJ/KG
OUTPUT DATA:
MASS BALANCE(KG/HR):  C       H       O       N      OVERALL
  AIR                                32.66  108.14  140.75
  DRY FUEL          40.29    5.09    36.10           90.93
  FUEL MOISTURE              0.98     7.84            9.77
  DRY GAS           31.66    3.12    53.06  108.12  196.03
  GAS MOISTURE               3.25    26.06           29.32
  CHAR               6.72    0.07     0.01           14.30
  FLY ASH            0.42    0.01     0.01            0.80
  CLOSURE(%)         3.71   -6.32    -3.32    0.02    0.41
DRY GAS VOLUME FLOWRATE           3.00 M3/MIN
MOLEC. WT.-DRY GAS               26.156
DENSITY- DRY GAS                  1.088 KG/M3
GAS WATER VAPOR MASS FRACTION    14.96 % DRY BASIS
STOICH AIR          MASS BASIS    5.33 KG/KG FUEL
                  VOLUME BASIS    6.70 M3/MIN        29.06 %
AIR/FUEL RATIO                    1.40
ENERGY BALANCE:
GAS HHV AT 298 K                  5.214 MJ/M3     139.95 BTU/FT3
GAS LHV AT 298 K                  4.833 MJ/M3     129.71 BTU/FT3
DRY FUEL ENERGY-HHV            1556.36 MJ/HR
                LHV            1442.65 MJ/HR
ENERGY IN CHAR                  217.65 MJ/HR       13.98 %
ENERGY IN FLY ASH                14.74 MJ/HR        0.95 %
SENSIBLE ENERGY IN GAS          217.59 MJ/HR       13.98 %
CHEMICAL ENERGY IN GAS          939.81 MJ/HR       60.39 %
ENERGY LOSSES                   166.57 MJ/HR       10.70 %
EFFICIENCY             HOT GAS   69.95 %
                      COLD GAS   55.97 %
```

```
C.E. GASIFIER RUN 40
INPUT DATA:
TEMPERATURE FOR FLOW RATES       293.00 K
SAT VAPOR PRESSURE AT THIS T      23.62 MILLIBARS
AIR VOLUME FLOW RATE               2.01 M3/MIN
COMPOSITION(% DRY WT):          FUEL      CHAR    FLY ASH
                       C      45.510    55.440    61.870
                       H       5.800     0.550     0.730
                       O      44.210     1.470     1.390
ENTHALPY HHV(MJ/KG)           19.020    19.900    21.290
MASS FLOWRATE(WET KG/HR)     100.900    13.900     0.730
FUEL MOISTURE CONTENT              9.90 % DRY BASIS
DRY GAS COMPOSITION (% VOL):
                         CO      20.89
                         CO2     13.50
                         CH4      4.26
                         C2H      1.83
                         H2      15.50
                         N2      44.02
                         O2       0.00
CONDENSER WATER PRODUCTION RATE 125.000 G/M3 DRY GAS
GAS TEMPERATURE                 855.00 K
HOT GAS SAT VAPOR ENTHALPY        3.664 MJ/KG
OUTPUT DATA:
MASS BALANCE(KG/HR):  C        H        O        N       OVERALL
  AIR                                 33.61   111.30    144.87
  DRY FUEL           41.37     5.27   40.19              90.91
  FUEL MOISTURE                1.00    8.00               9.99
  DRY GAS            45.58     4.97   68.78   111.28    230.71
  GAS MOISTURE                 3.42   27.42              30.84
  CHAR                7.71     0.08    0.20              13.90
  FLY ASH             0.45     0.01    0.01               0.73
  CLOSURE(%)        -29.88   -35.11  -17.86     0.02    -12.38
DRY GAS VOLUME FLOWRATE           3.60 M3/MIN
MOLEC. WT.-DRY GAS              25.700
DENSITY- DRY GAS                 1.069 KG/M3
GAS WATER VAPOR MASS FRACTION   13.37 % DRY BASIS
STOICH AIR          MASS BASIS   5.34 KG/KG FUEL
                  VOLUME BASIS   6.72 M3/MIN       29.84 %
AIR/FUEL RATIO                   1.44
ENERGY BALANCE:
GAS HHV AT 298 K                 6.955 MJ/M3      186.68 BTU/FT3
GAS LHV AT 298 K                 6.449 MJ/M3      173.08 BTU/FT3
DRY FUEL ENERGY-HHV           1728.96 MJ/HR
                LHV           1604.37 MJ/HR
ENERGY IN CHAR                 276.61 MJ/HR        16.00 %
ENERGY IN FLY ASH               15.54 MJ/HR         0.90 %
SENSIBLE ENERGY IN GAS         242.31 MJ/HR        14.01 %
CHEMICAL ENERGY IN GAS        1501.63 MJ/HR        86.85 %
ENERGY LOSSES                 -307.13 MJ/HR       -17.76 %
EFFICIENCY             HOT GAS  94.54 %
                      COLD GAS  80.52 %
```

```
C.E. GASIFIER RUN 41
INPUT DATA:
TEMPERATURE FOR FLOW RATES       293.00 K
SAT VAPOR PRESSURE AT THIS T      23.62 MILLIBARS
AIR VOLUME FLOW RATE               1.96 M3/MIN
COMPOSITION(% DRY WT):         FUEL      CHAR    FLY ASH
                      C      44.770    55.940    60.630
                      H       5.690     0.590     0.710
                      O      43.300     1.200     0.990
ENTHALPY HHV(MJ/KG)          18.680    20.460    20.850
MASS FLOWRATE(WET KG/HR)    107.100    14.800     0.660
FUEL MOISTURE CONTENT              8.40 % DRY BASIS
DRY GAS COMPOSITION (% VOL):
                         CO       19.68
                         CO2      13.50
                         CH4       3.49
                         C2H       1.50
                         H2       15.85
                         N2       45.98
                         O2        0.00
CONDENSER WATER PRODUCTION RATE 123.024 G/M3 DRY GAS
GAS TEMPERATURE                 883.00 K
HOT GAS SAT VAPOR ENTHALPY        3.726 MJ/KG
OUTPUT DATA:
MASS BALANCE(KG/HR):  C        H        O        N      OVERALL
  AIR                                 32.84   108.75    141.54
  DRY FUEL          43.92     5.58    42.48              98.10
  FUEL MOISTURE               0.91     7.33               9.00
  DRY GAS           39.97     4.34    62.71   108.73    215.85
  GAS MOISTURE                3.16    25.29              28.45
  CHAR               8.28     0.09     0.18              14.80
  FLY ASH            0.40     0.00     0.01               0.66
  CLOSURE(%)       -10.78   -16.79    -6.71     0.02     -4.47
DRY GAS VOLUME FLOWRATE           3.37 M3/MIN
MOLEC. WT.-DRY GAS               25.704
DENSITY- DRY GAS                  1.069 KG/M3
GAS WATER VAPOR MASS FRACTION    13.18 % DRY BASIS
STOICH AIR           MASS BASIS   5.26 KG/KG FUEL
                   VOLUME BASIS   7.14 M3/MIN        27.45 %
AIR/FUEL RATIO                    1.32
ENERGY BALANCE:
GAS HHV AT 298 K                  6.376 MJ/M3      171.11 BTU/FT3
GAS LHV AT 298 K                  5.903 MJ/M3      158.42 BTU/FT3
DRY FUEL ENERGY-HHV            1832.40 MJ/HR
                LHV            1704.23 MJ/HR
ENERGY IN CHAR                  302.81 MJ/HR        16.53 %
ENERGY IN FLY ASH                13.76 MJ/HR         0.75 %
SENSIBLE ENERGY IN GAS          234.56 MJ/HR        12.80 %
CHEMICAL ENERGY IN GAS         1287.54 MJ/HR        70.27 %
ENERGY LOSSES                    -6.28 MJ/HR        -0.34 %
EFFICIENCY             HOT GAS   77.85 %
                      COLD GAS   65.05 %
```

```
C.E. GASIFIER RUN 42
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.00 K
SAT VAPOR PRESSURE AT THIS T     23.62 MILLIBARS
AIR VOLUME FLOW RATE              1.96 M3/MIN
COMPOSITION(% DRY WT):        FUEL      CHAR     FLY ASH
                       C     44.470    39.360    57.200
                       H      5.700     0.430     0.630
                       O     42.340     1.290     0.740
ENTHALPY HHV(MJ/KG)          17.990    15.600    20.310
MASS FLOWRATE(WET KG/HR)     99.700    14.800     0.710
FUEL MOISTURE CONTENT            10.20 % DRY BASIS
DRY GAS COMPOSITION (% VOL):
                         CO      19.83
                         CO2     13.50
                         CH4      2.79
                         C2H      1.19
                         H2      16.14
                         N2      46.55
                         O2       0.00
CONDENSER WATER PRODUCTION RATE 126.109 G/M3 DRY GAS
GAS TEMPERATURE                 863.00 K
HOT GAS SAT VAPOR ENTHALPY       3.682 MJ/KG
OUTPUT DATA:
MASS BALANCE(KG/HR):  C       H       O        N      OVERALL
  AIR                                32.93   109.03   141.90
  DRY FUEL          39.81    5.10    37.91             89.53
  FUEL MOISTURE              1.01     8.12             10.17
  DRY GAS           38.42    4.01    62.30   109.01   213.82
  GAS MOISTURE               3.20    25.59             28.79
  CHAR               5.83    0.06     0.19             14.80
  FLY ASH            0.41    0.00     0.01              0.71
  CLOSURE(%)       -12.15  -18.87   -11.58     0.02    -6.84
DRY GAS VOLUME FLOWRATE          3.33 M3/MIN
MOLEC. WT.-DRY GAS              25.713
DENSITY- DRY GAS                 1.069 KG/M3
GAS WATER VAPOR MASS FRACTION   13.46 % DRY BASIS
STOICH AIR           MASS BASIS   5.27 KG/KG FUEL
                   VOLUME BASIS   6.53 M3/MIN       30.10 %
AIR/FUEL RATIO                   1.42
ENERGY BALANCE:
GAS HHV AT 298 K                 5.986 MJ/M3      160.67 BTU/FT3
GAS LHV AT 298 K                 5.545 MJ/M3      148.83 BTU/FT3
DRY FUEL ENERGY-HHV           1610.41 MJ/HR
                LHV           1491.21 MJ/HR
ENERGY IN CHAR                 230.88 MJ/HR        14.34 %
ENERGY IN FLY ASH               14.42 MJ/HR         0.90 %
SENSIBLE ENERGY IN GAS         225.39 MJ/HR        14.00 %
CHEMICAL ENERGY IN GAS        1197.20 MJ/HR        74.34 %
ENERGY LOSSES                  -57.48 MJ/HR        -3.57 %
EFFICIENCY              HOT GAS  82.86 %
                       COLD GAS  68.86 %
```

```
C.E. GASIFIER RUN 44
INPUT DATA:
TEMPERATURE FOR FLOW RATES          293.00 K
SAT VAPOR PRESSURE AT THIS T         23.62 MILLIBARS
AIR VOLUME FLOW RATE                  1.92 M3/MIN
COMPOSITION(% DRY WT):           FUEL      CHAR     FLY ASH
                       C       46.320    57.600    57.750
                       H        5.750     0.500     0.670
                       O       44.670     5.500     0.480
ENTHALPY HHV(MJ/KG)            19.430    19.970    20.730
MASS FLOWRATE(WET KG/HR)      102.700    14.400     0.280
FUEL MOISTURE CONTENT                6.50 % DRY BASIS
DRY GAS COMPOSITION (% VOL):
                          CO       20.04
                          CO2      14.29
                          CH4       3.39
                          C2H       1.03
                          H2       16.59
                          N2       44.66
                          O2        0.00
CONDENSER WATER PRODUCTION RATE  93.620 G/M3 DRY GAS
GAS TEMPERATURE                 875.00 K
HOT GAS SAT VAPOR ENTHALPY         3.708 MJ/KG
OUTPUT DATA:
MASS BALANCE(KG/HR):  C        H        O         N      OVERALL
  AIR                                 32.19    106.58    138.72
  DRY FUEL          44.48     5.52    42.89               96.02
  FUEL MOISTURE               0.69     5.55                6.68
  DRY GAS           40.45     4.31    65.91    106.56    217.33
  GAS MOISTURE                2.52    20.20               22.72
  CHAR               8.29     0.07     0.79               14.40
  FLY ASH            0.16     0.00     0.00                0.28
  CLOSURE(%)        -9.95   -11.11    -7.77      0.02     -5.51
DRY GAS VOLUME FLOWRATE            3.40 M3/MIN
MOLEC. WT.-DRY GAS                25.648
DENSITY- DRY GAS                   1.067 KG/M3
GAS WATER VAPOR FRACTION          10.45% DRY BASIS
STOICH AIR           MASS BASIS    5.40 KG/KG FUEL
                   VOLUME BASIS    7.17 M3/MIN          26.77 %
AIR/FUEL RATIO                     1.35
ENERGY BALANCE:
GAS HHV AT 298 K                   6.193 MJ/M3      166.21 BTU/FT3
GAS LHV AT 298 K                   5.727 MJ/M3      153.72 BTU/FT3
DRY FUEL ENERGY-HHV             1865.65 MJ/HR
                LHV             1741.67 MJ/HR
ENERGY IN CHAR                   287.57 MJ/HR        15.41 %
ENERGY IN FLY ASH                  5.80 MJ/HR         0.31 %
SENSIBLE ENERGY IN GAS           217.30 MJ/HR        11.65 %
CHEMICAL ENERGY IN GAS          1262.01 MJ/HR        67.64 %
ENERGY LOSSES                     92.97 MJ/HR         4.98 %
EFFICIENCY             HOT GAS    74.21 %
                      COLD GAS    62.56 %
```

```
C.E. GASIFIER RUN 44GC
INPUT DATA:
TEMPERATURE FOR FLOW RATES        293.00 K
SAT VAPOR PRESSURE AT THIS T       23.62 MILLIBARS
AIR VOLUME FLOW RATE                1.92 M3/MIN
COMPOSITION(% DRY WT):            FUEL      CHAR    FLY ASH
                        C       46.320    57.600    57.750
                        H        5.750     0.500     0.670
                        O       44.670     5.500     0.480
ENTHALPY HHV(MJ/KG)             19.430    19.970    20.730
MASS FLOWRATE(WET KG/HR)       102.700    14.400     0.280
FUEL MOISTURE CONTENT                6.50 % DRY BASIS
DRY GAS COMPOSITION (% VOL):
                           CO       19.88
                           CO2      10.79
                           CH4       2.69
                           C2H       0.82
                           H2       15.79
                           N2       49.19
                           O2        0.84
CONDENSER WATER PRODUCTION RATE  93.620 G/M3 DRY GAS
GAS TEMPERATURE                  875.00 K
HOT GAS SAT VAPOR ENTHALPY         3.708 MJ/KG
OUTPUT DATA:
MASS BALANCE(KG/HR):  C        H        O        N      OVERALL
  AIR                                 32.19   106.58   138.72
  DRY FUEL          44.48     5.52    42.89             96.02
  FUEL MOISTURE               0.69     5.55              6.68
  DRY GAS           32.31     3.51    51.03   106.56   195.56
  GAS MOISTURE                2.29    18.34             20.62
  CHAR               8.29     0.07     0.79             14.40
  FLY ASH            0.16     0.00     0.00              0.28
  CLOSURE(%)         8.34     5.50    12.99     0.02     4.37
DRY GAS VOLUME FLOWRATE            3.08 M3/MIN
MOLEC. WT.-DRY GAS                25.420
DENSITY- DRY GAS                   1.057 KG/M3
GAS WATER VAPOR MASS FRACTION     10.55 % DRY BASIS
STOICH AIR          MASS BASIS     5.40 KG/KG FUEL
                  VOLUME BASIS     7.17 M3/MIN         26.77 %
AIR/FUEL RATIO                     1.35
ENERGY BALANCE:
GAS HHV AT 298 K                   5.696 MJ/M3      152.89 BTU/FT3
GAS LHV AT 298 K                   5.279 MJ/M3      141.68 BTU/FT3
DRY FUEL ENERGY-HHV             1865.65 MJ/HR
                LHV             1741.67 MJ/HR
ENERGY IN CHAR                   287.57 MJ/HR        15.41 %
ENERGY IN FLY ASH                  5.80 MJ/HR         0.31 %
SENSIBLE ENERGY IN GAS           193.87 MJ/HR        10.39 %
CHEMICAL ENERGY IN GAS          1053.91 MJ/HR        56.49 %
ENERGY LOSSES                    324.50 MJ/HR        17.39 %
EFFICIENCY               HOT GAS  62.74 %
                        COLD GAS  52.35 %
```

APPENDIX C

AGRICULTURAL ENGINEERING DATA ACQUISITION

A data acquisition system was developed for a fluidized bed gasifier by the UCD Agriculture Engineering Department. This data acquisition system was used for this project to sample and record gasification system temperatures and producer gas composition values for all runs and various pressure measurements for Runs 40, 41 and 42. A brief description of the data acquisition system is cited below. For complete information on this system see Reference 21.

The data acquisition system consisting of a Digital Equipment Corporation (DEC) LSI-11/2 computer and Hewlett-Packard Digital Voltmeter 3465A and Scanner 3495A was used to sample temperature, pressure and gas composition. The voltmeter and scanner are connected to the computer by a Hewlett-Packard Interface Bus and a DEC IBV11-A Instrument Bus Interface. Fortran subroutines are used to open and close channels, trigger measurements and transfer data. An interactive data acquisition program (listed as "SAM") measure either voltage or resistance on up to 40 channels and stores data as volts or ohms in a file on a floppy disk via a Data Systems Designs 4140 Floppy Disk Drive. Sampled data as volts or ohms and converted to temperatures, pressures or gas composition are continuously displayed on a Micro-Term MIKE 2A terminal while running "SAM". An interactive data processing program (listed as "PRO") which is run after terminating the program "SAM" reads the data file, converts the data and outputs data on the terminal, in another disk file or on a DEC Decwriter 4 printer.

APPENDIX D

TEMPERATURE, PRESSURE, AND GAS COMPOSITION DATA AS A FUNCTION OF TIME

Plots showing the variation of temperature, pressure, and gas composition data throughout each gasifier run are presented.

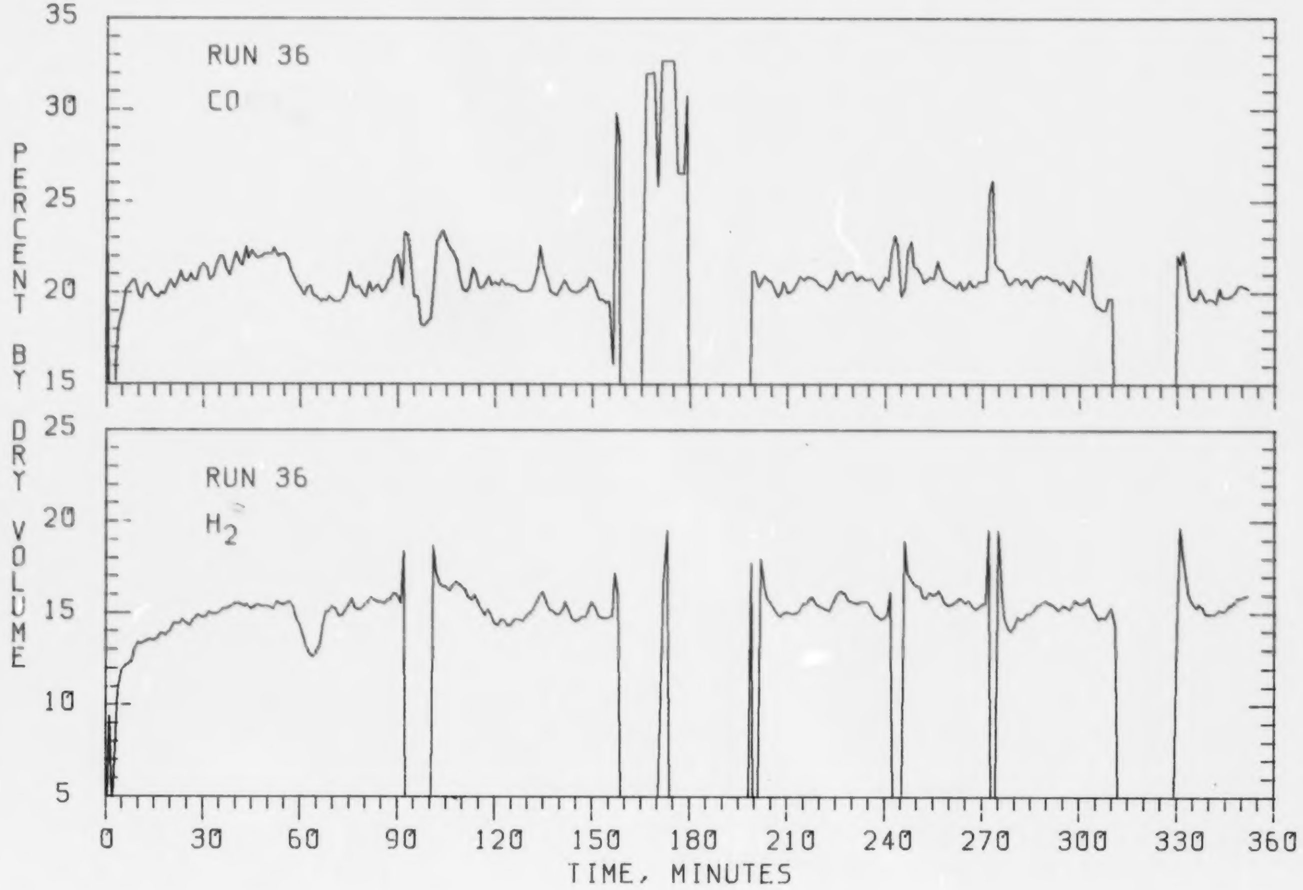

Figure D-1. CO and H_2 concentration variations throughout Run 36.

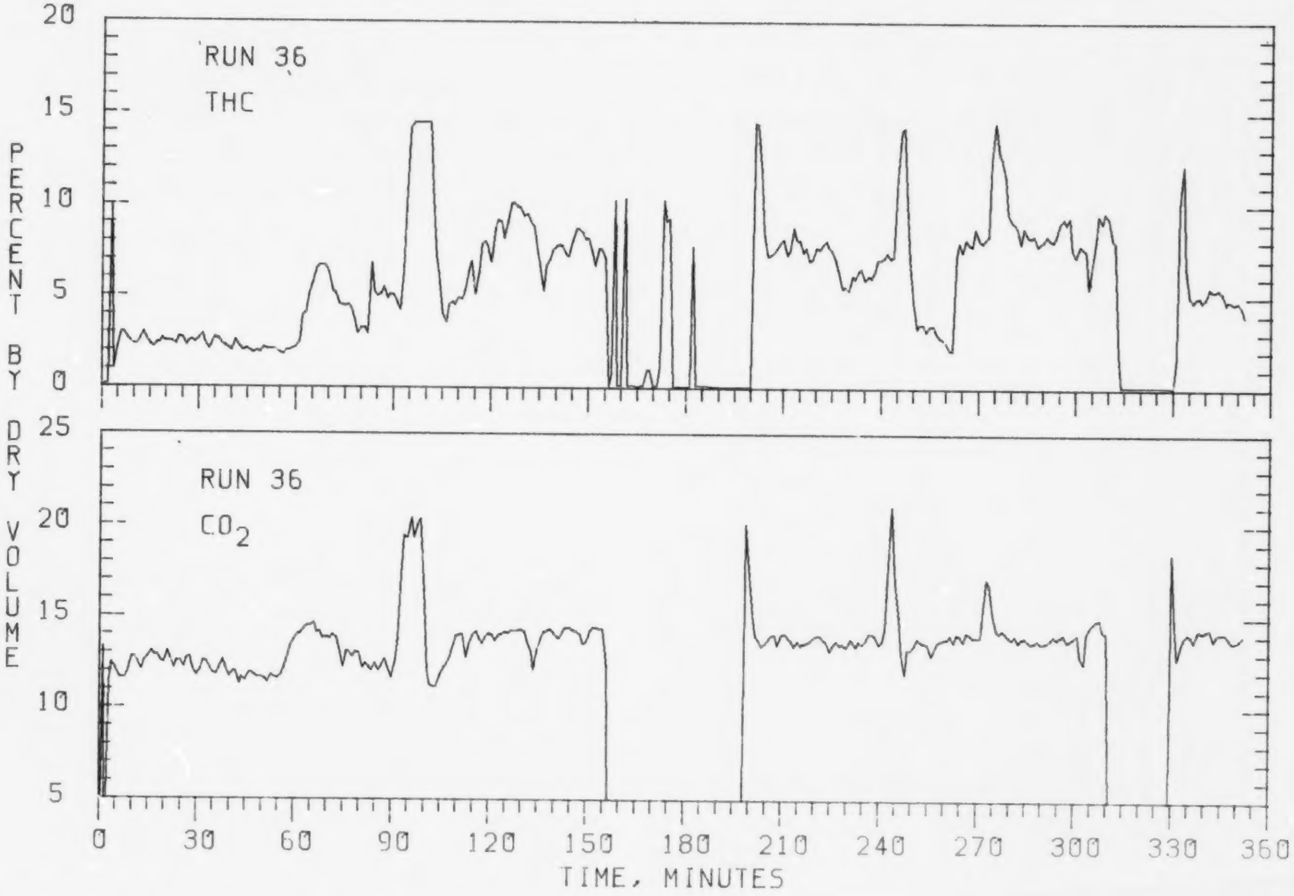

Figure D-2. THC and CO_2 concentration variation throughout Run 36.

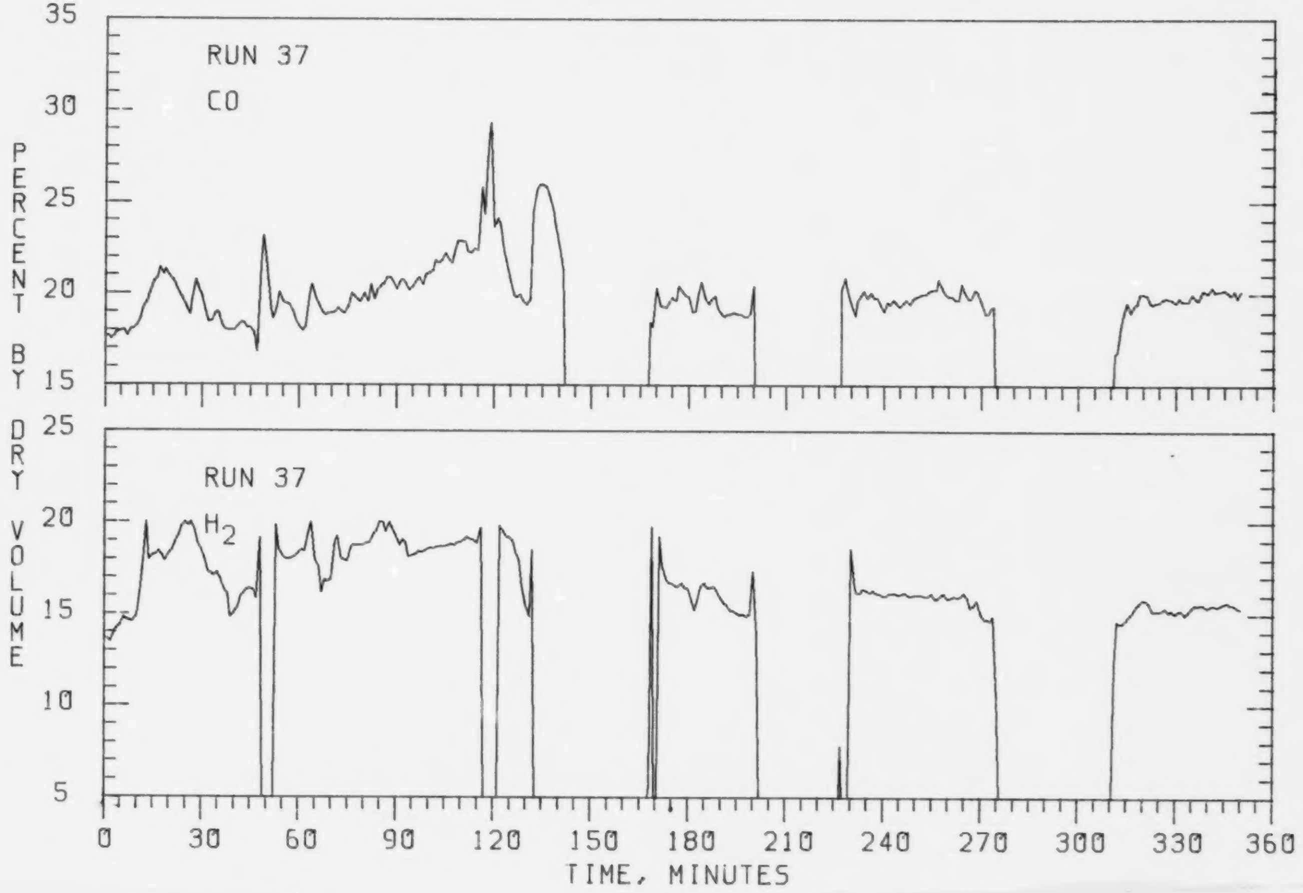

Figure D-3. CO and H_2 concentration variation throughout Run 37.

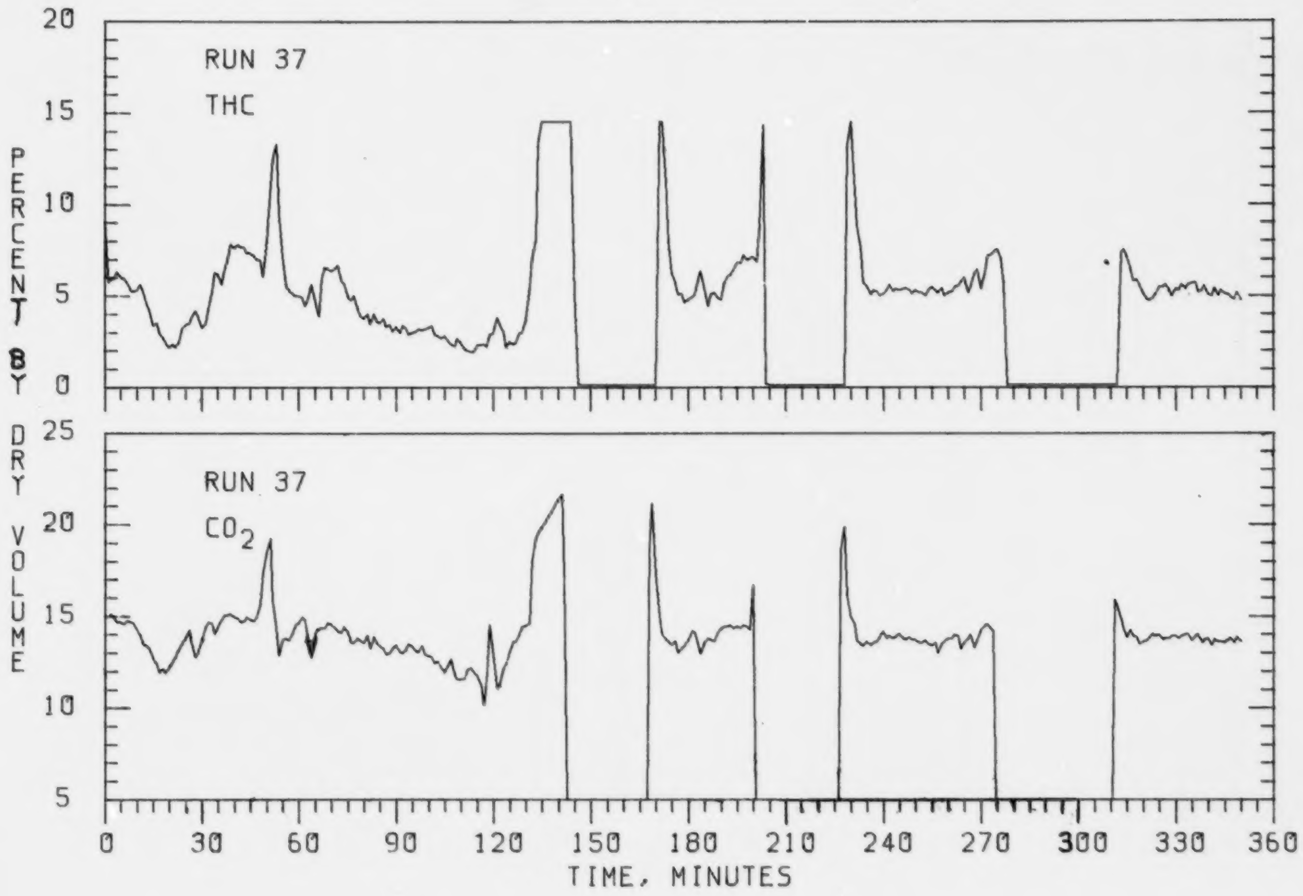

Figure D-4. THC and CO_2 concentration variations throughout Run 37.

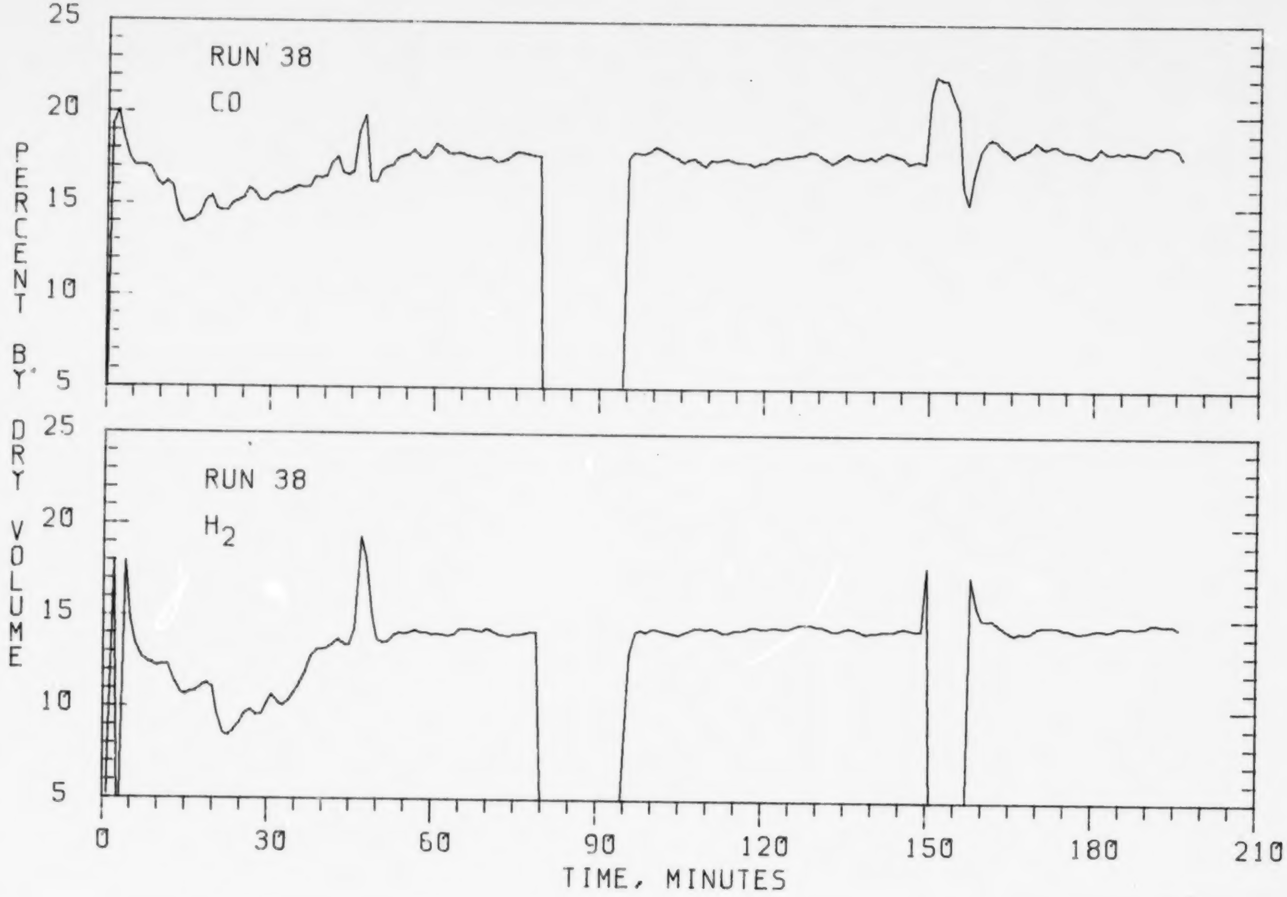

Figure D-5. CO and H_2 concentration variations throughout Run 38.

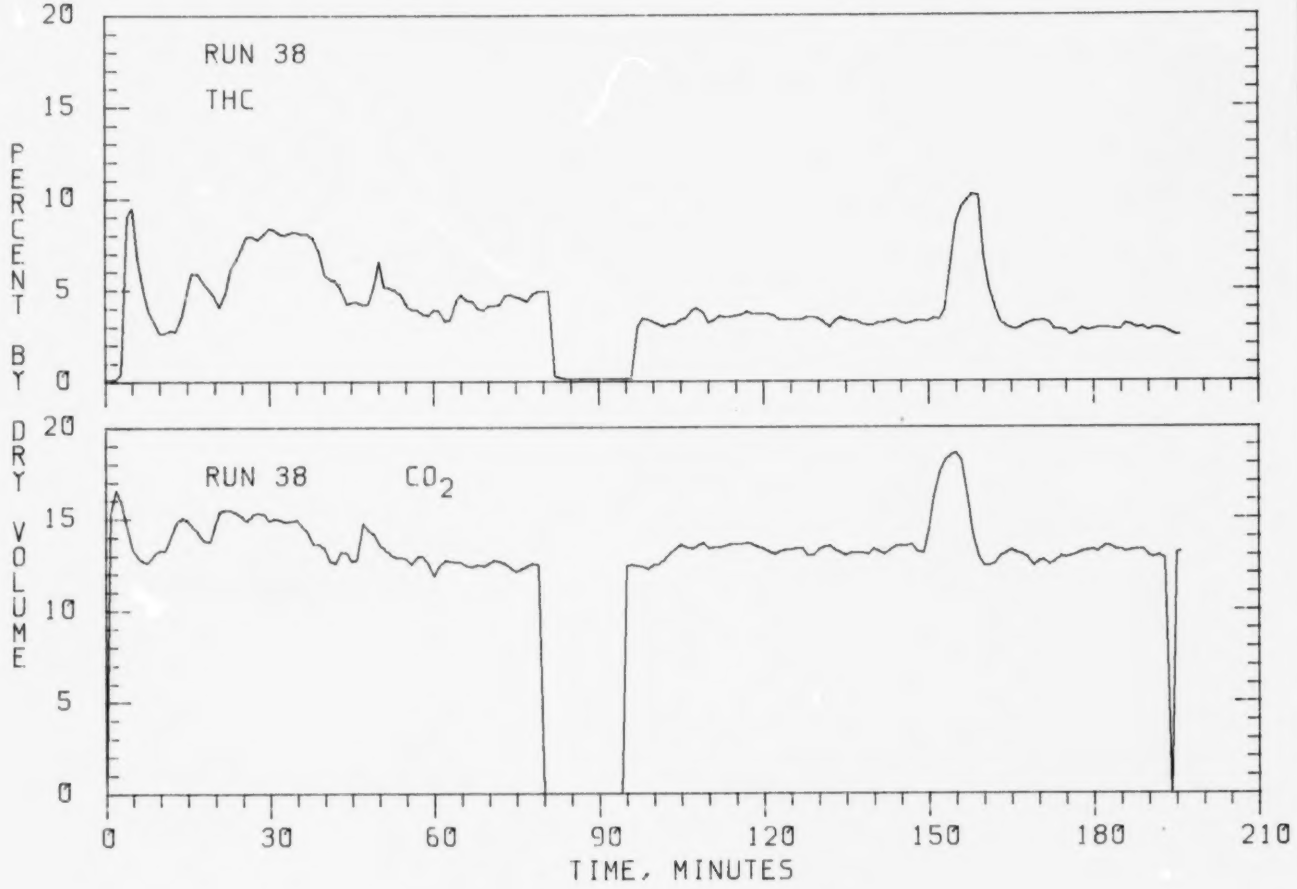

Figure D-6. THC and CO_2 concentration variations throughout Run 38.

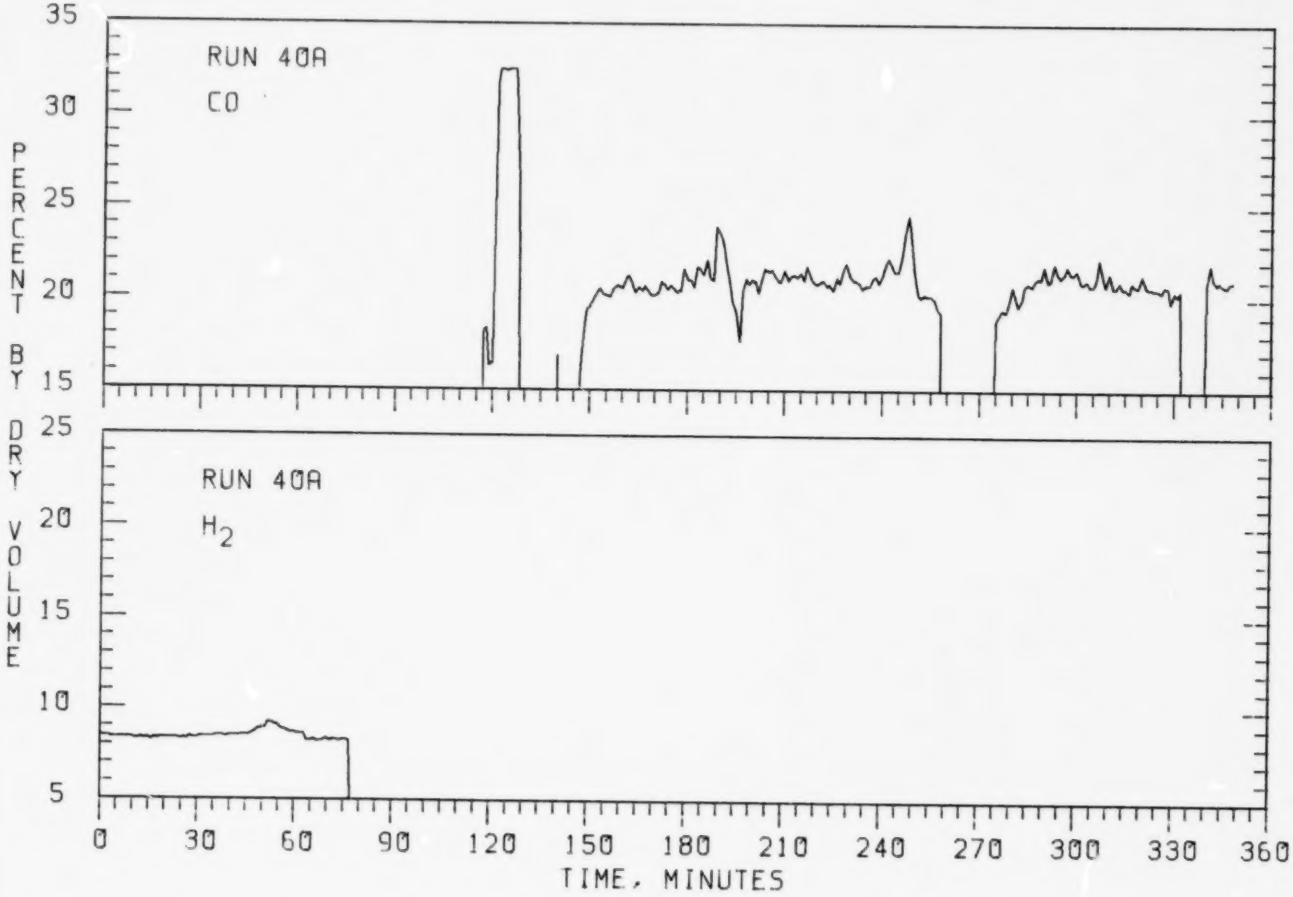

Figure D-7. CO and H_2 concentration variations throughout Run 40.

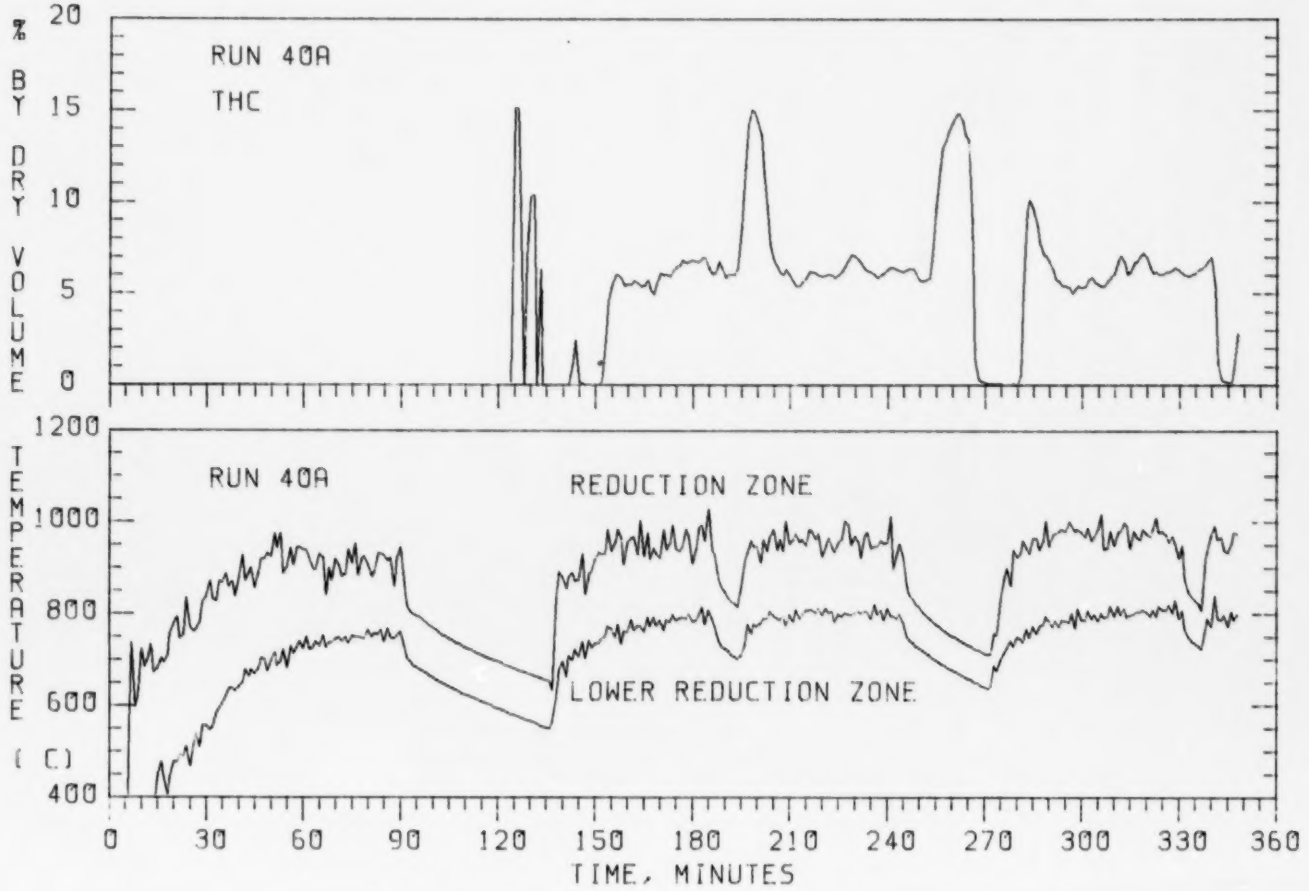

Figure D-8. THC concentration, reduction zone and lower reduction zone temperature variations throughout Run 40.

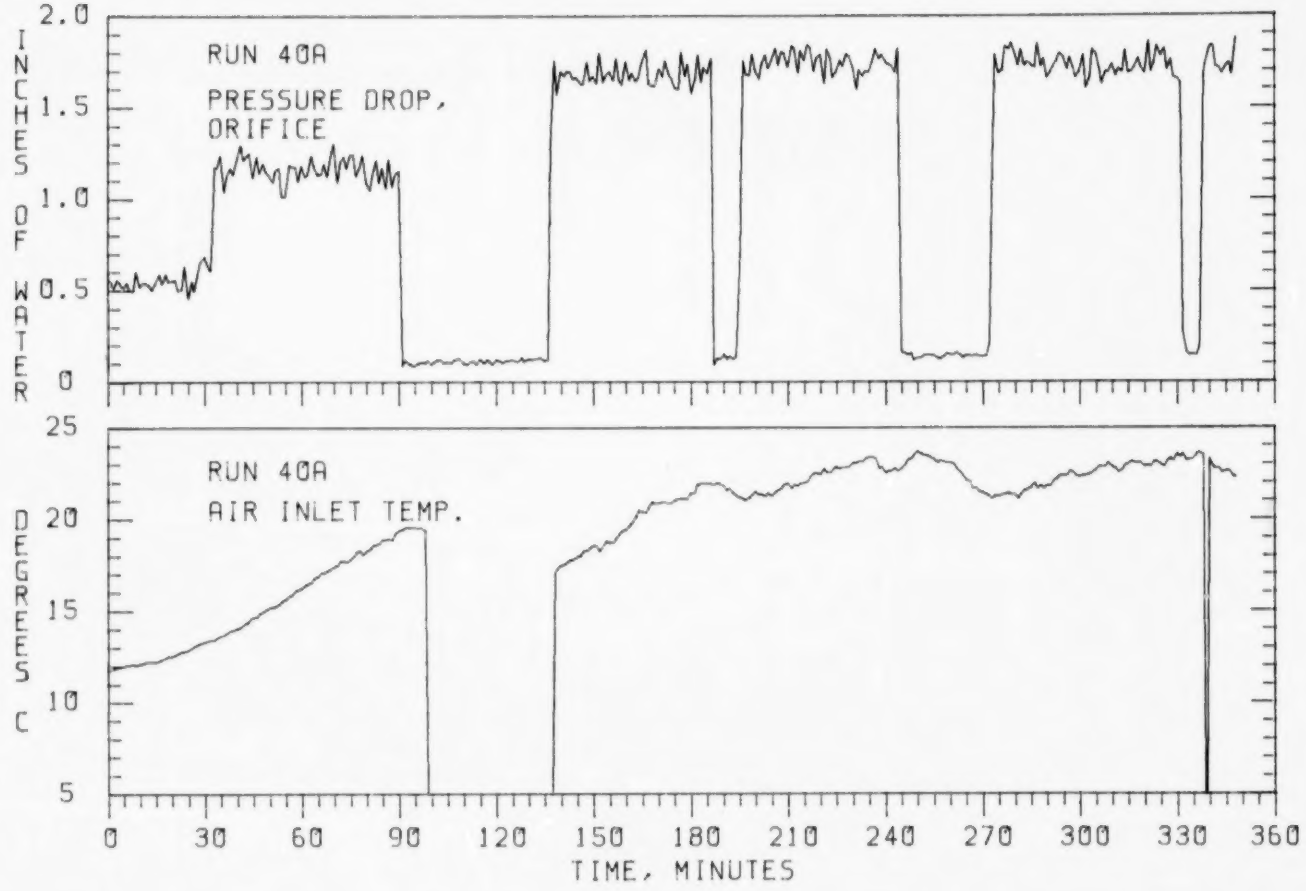

Figure D-9. Air inlet orifice plate pressure drop, air inlet temperature variations throughout Run 40.

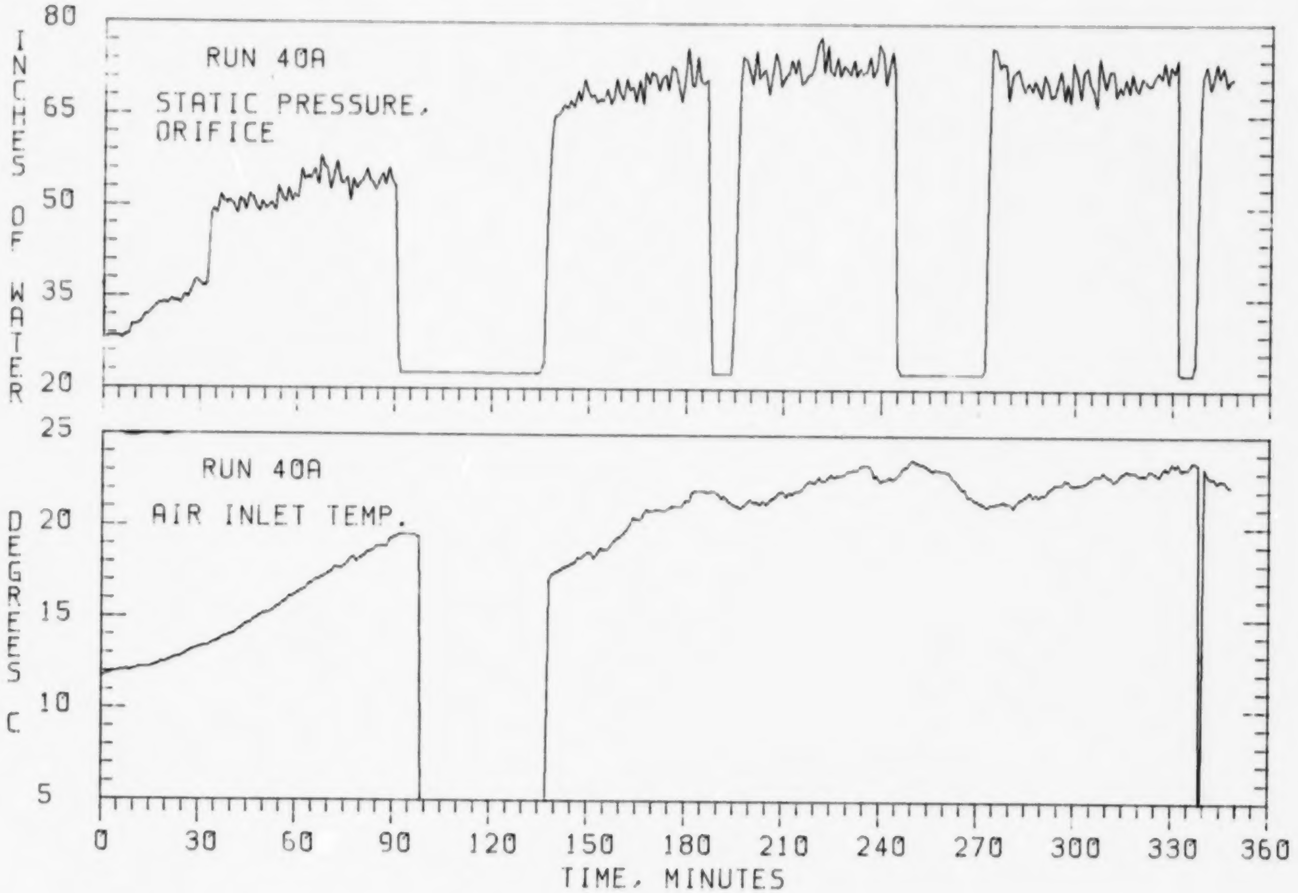

Figure D-10. Air inlet static pressure, air inlet temperature variations throughout Run 40.

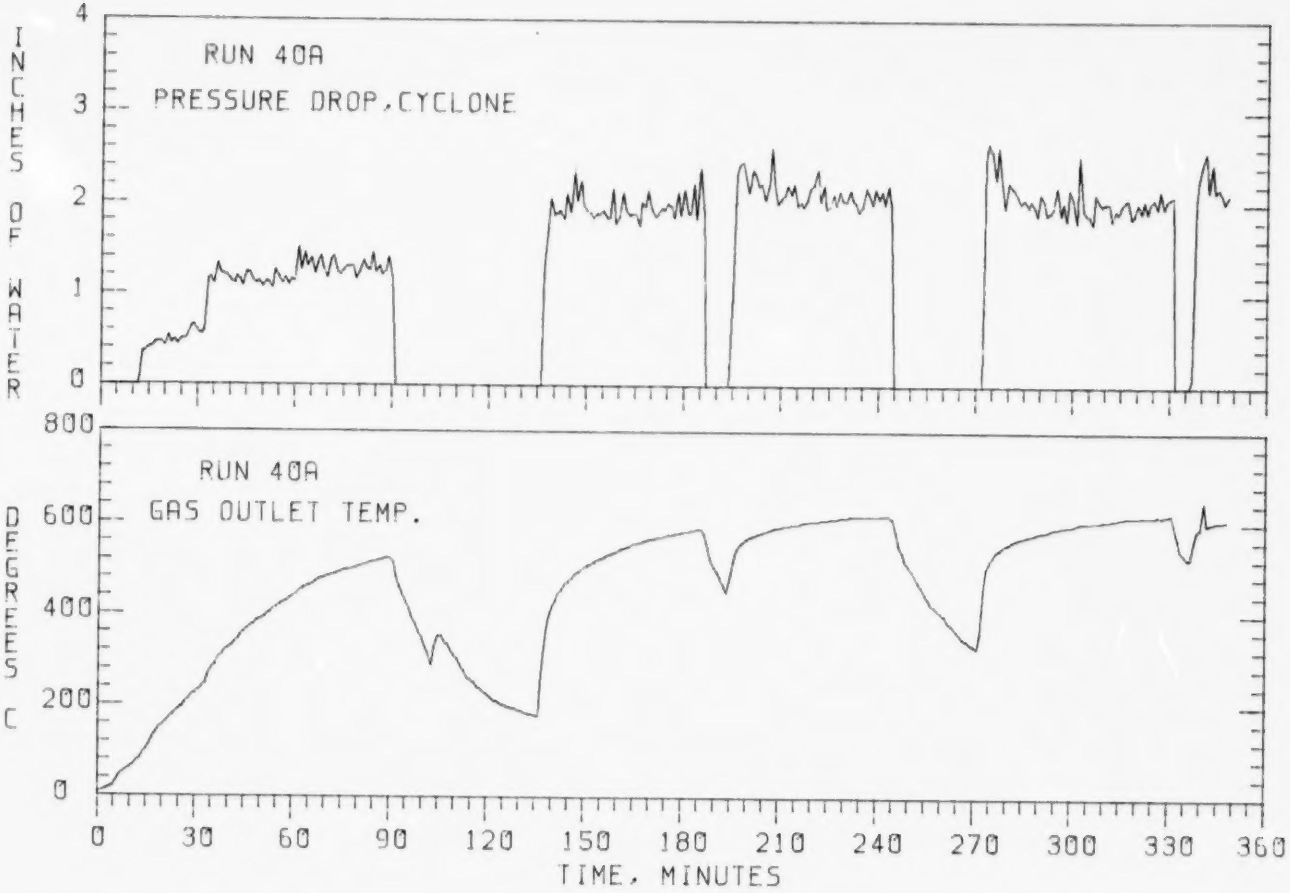

Figure D-11. High efficiency cyclone pressure drop, gas outlet temperature variations throughout Run 40.

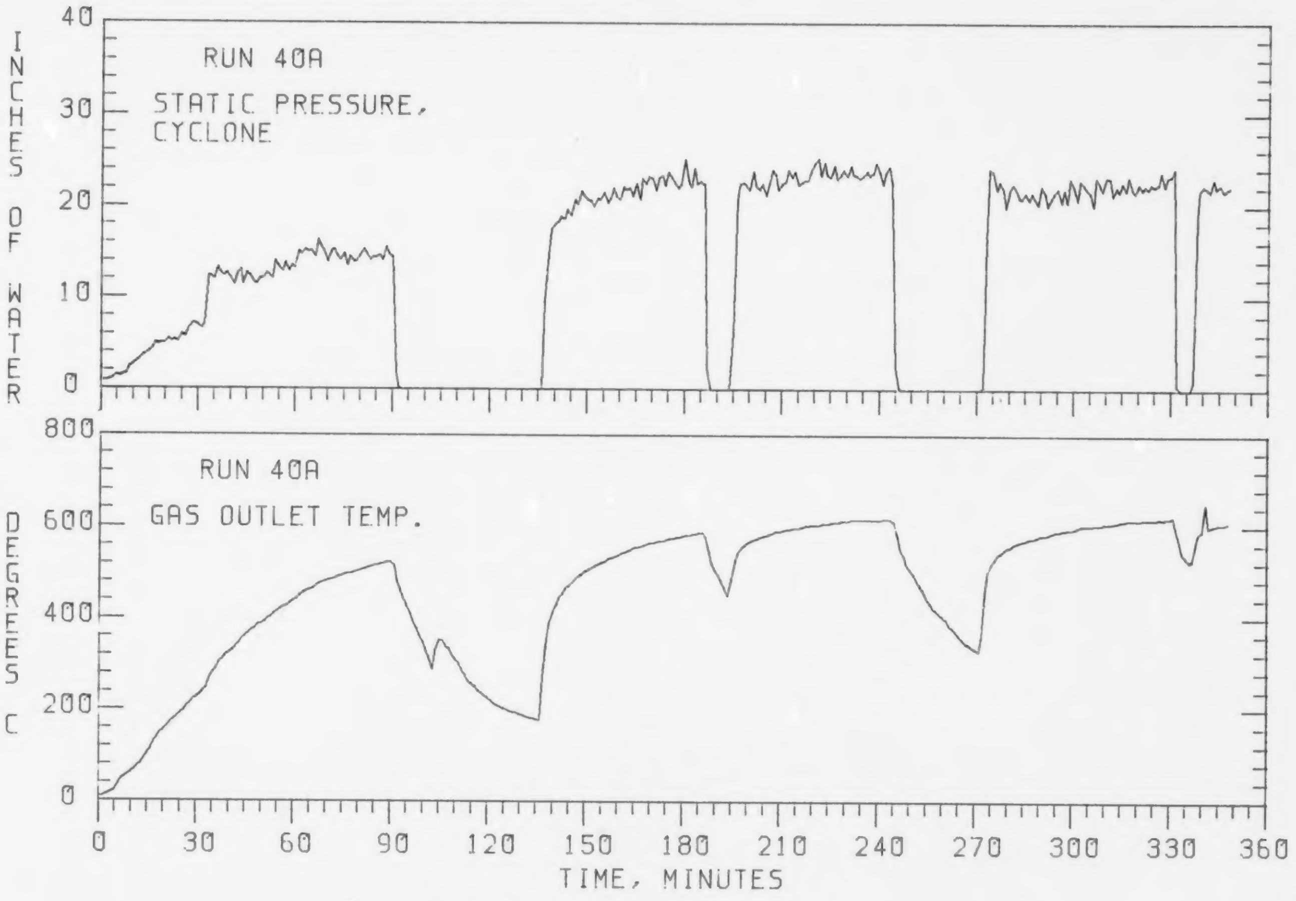

Figure D-12. Gas outlet static pressure, gas outlet temperature variations throughout Run 40.

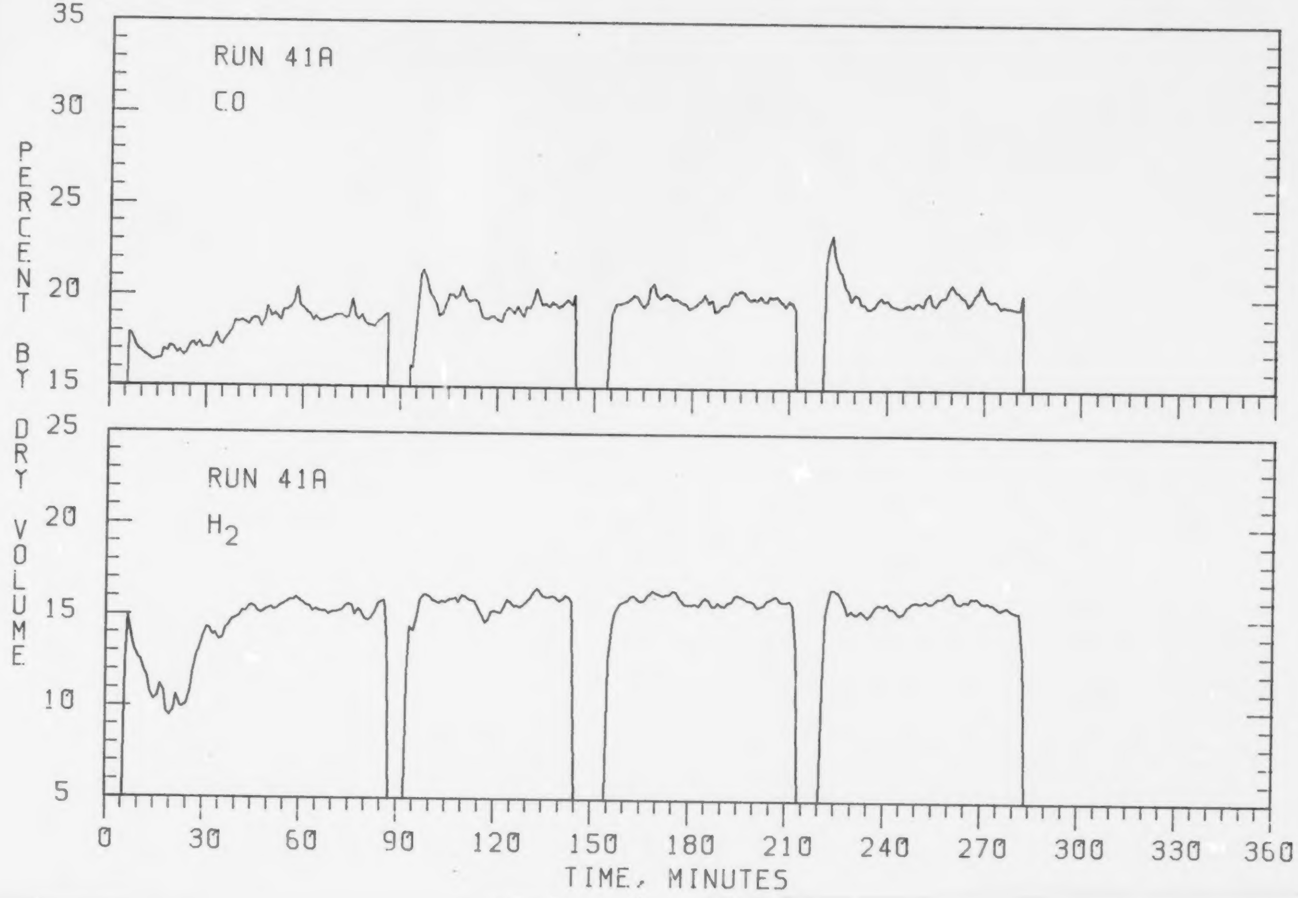

Figure D-13. CO and H_2 concentration variations throughout Run 41A.

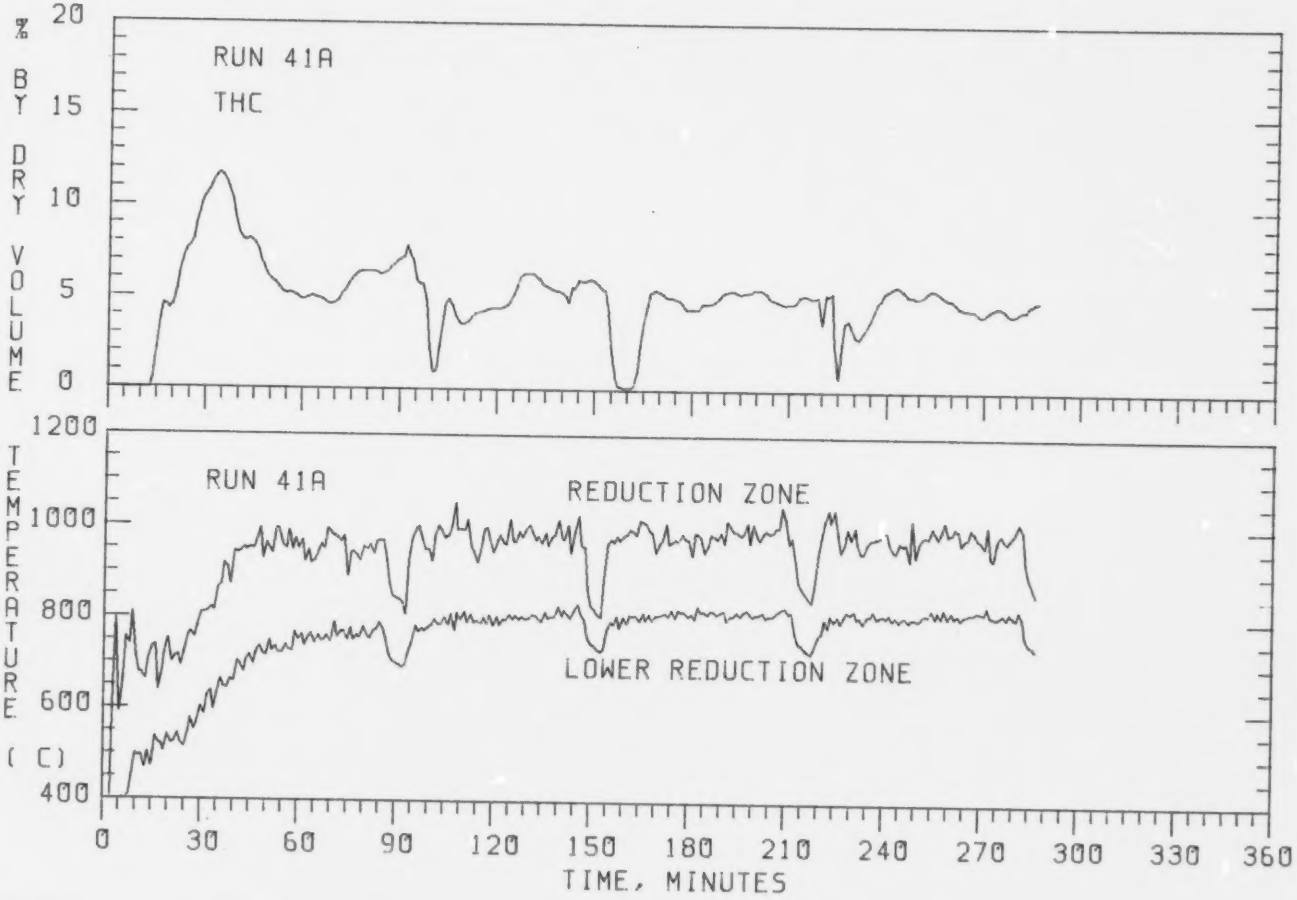

Figure D-14. THC concentration, reduction zone and lower reduction zone temperature variations throughout Run 41A.

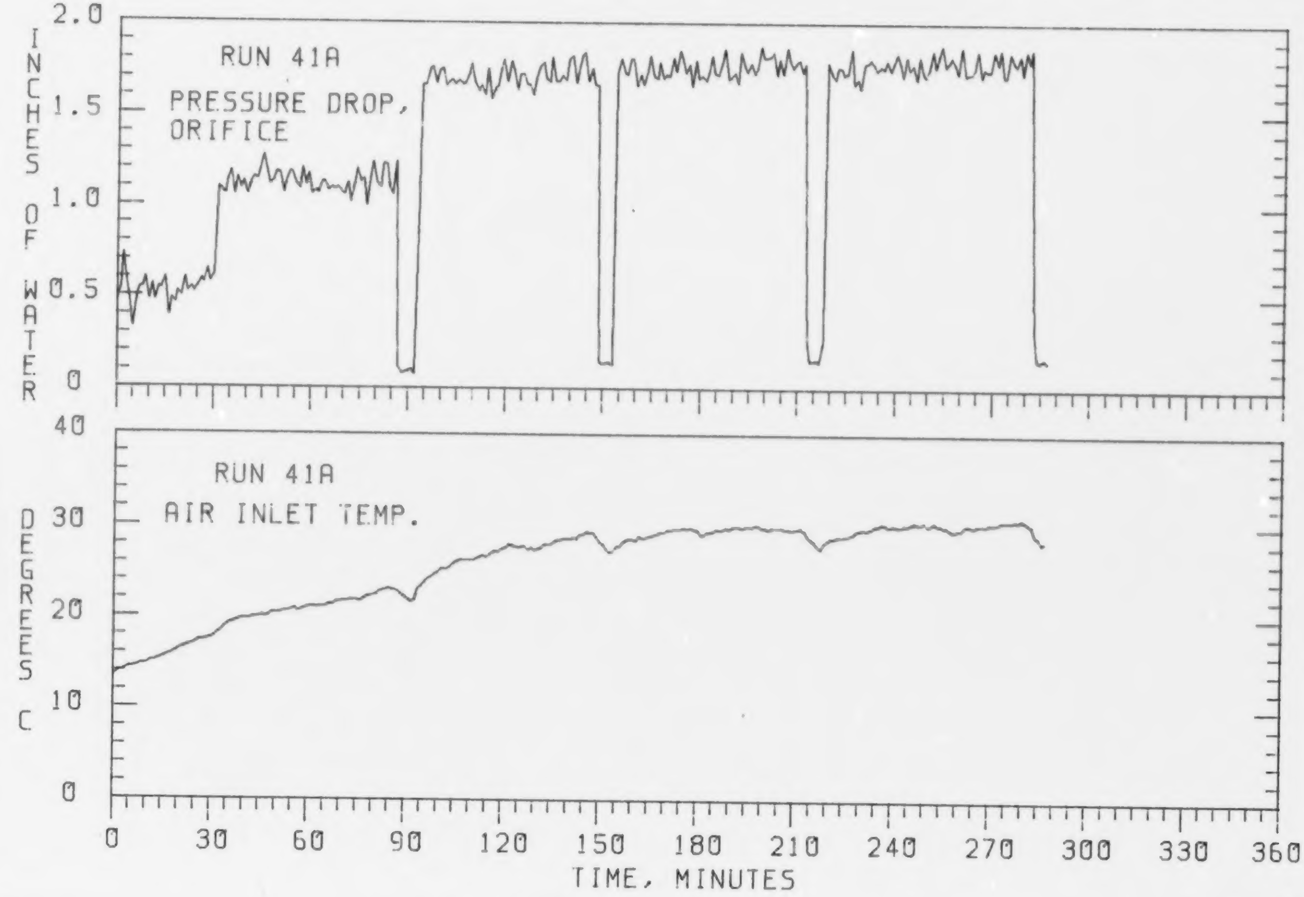

Figure D-15. Air inlet orifice plate pressure drop, air inlet temperature variations throughout Run 41A.

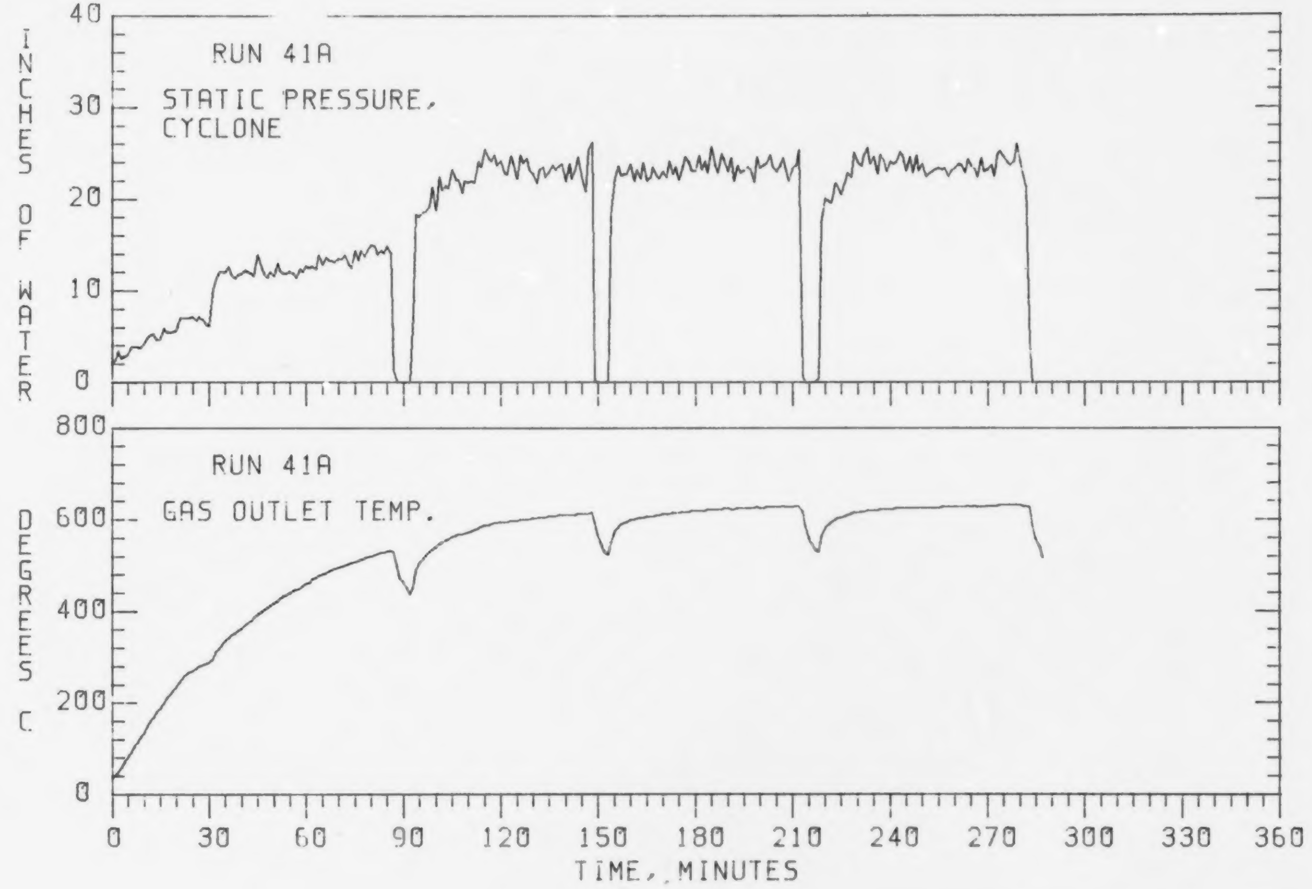

Figure D-16. Gas outlet static pressure and temperature variations throughout Run 41A.

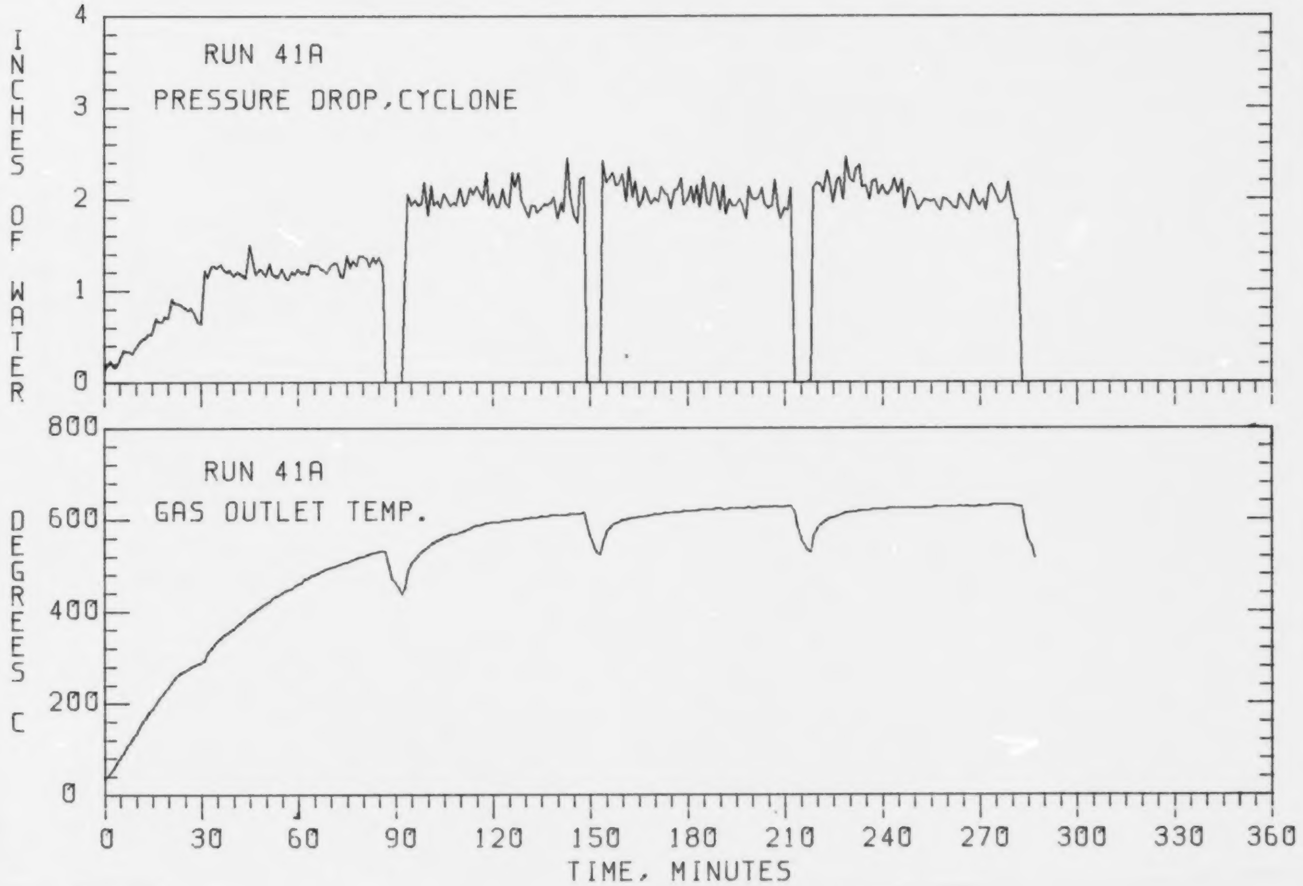

Figure D-17. High efficiency cyclone pressure drop, gas outlet temperature variations throughout Run 41A.

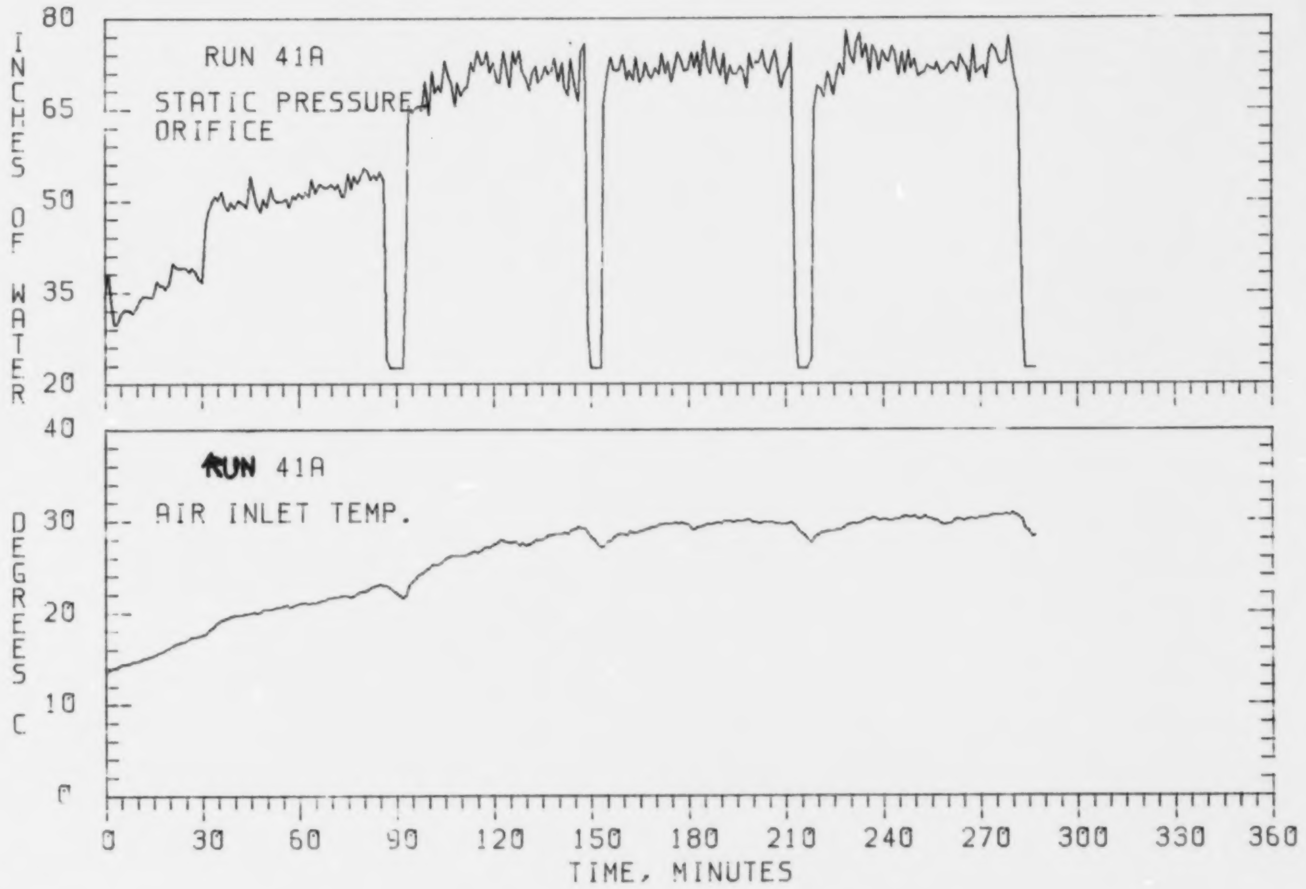

Figure D-18. Air inlet pressure drop and air inlet temperature variations throughout Run 41A.

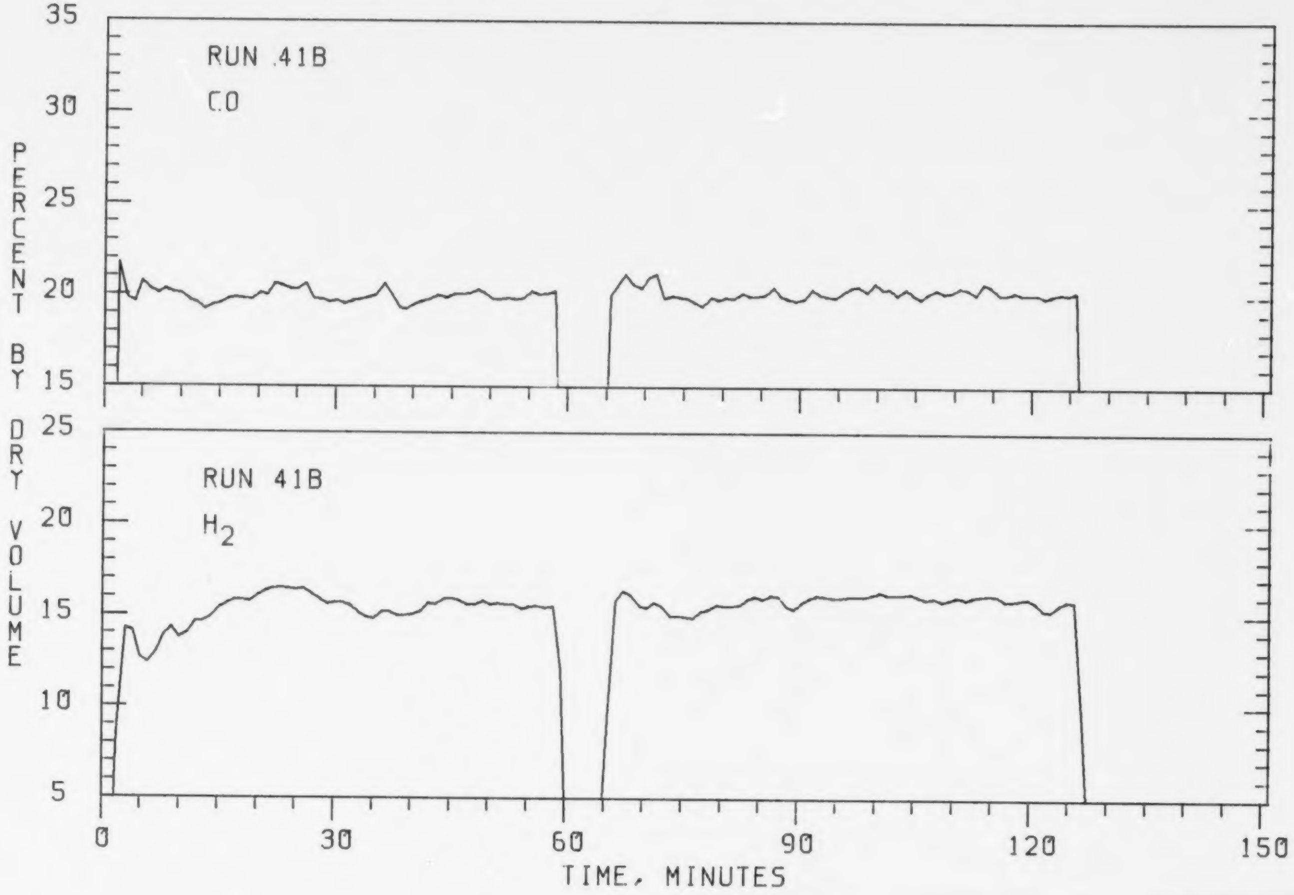

Figure D-19. CO and H_2 concentration variations throughout Run 41B.

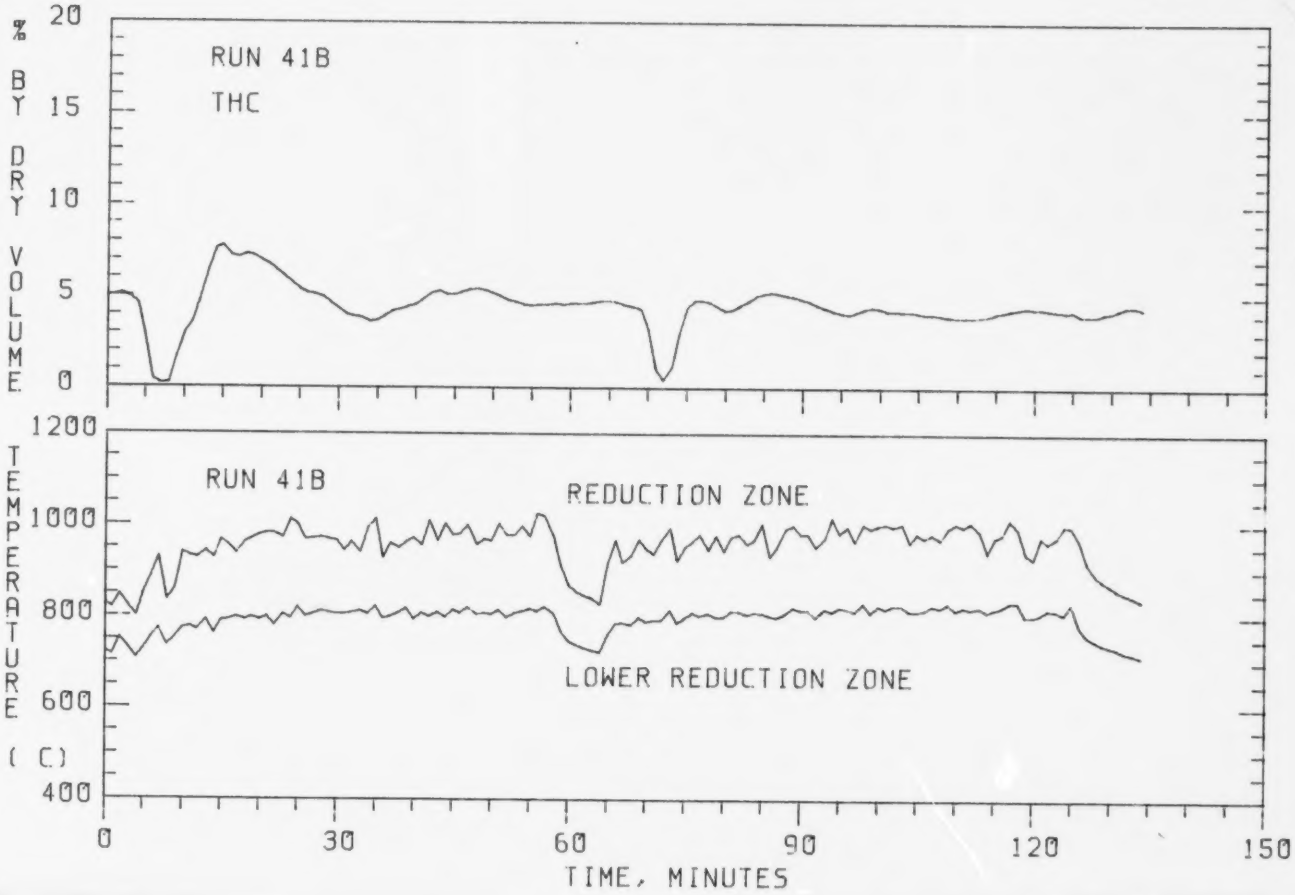

Figure D-20. THC concentration, reduction zone and lower reduction zone temperature variations throughout Run 41B.

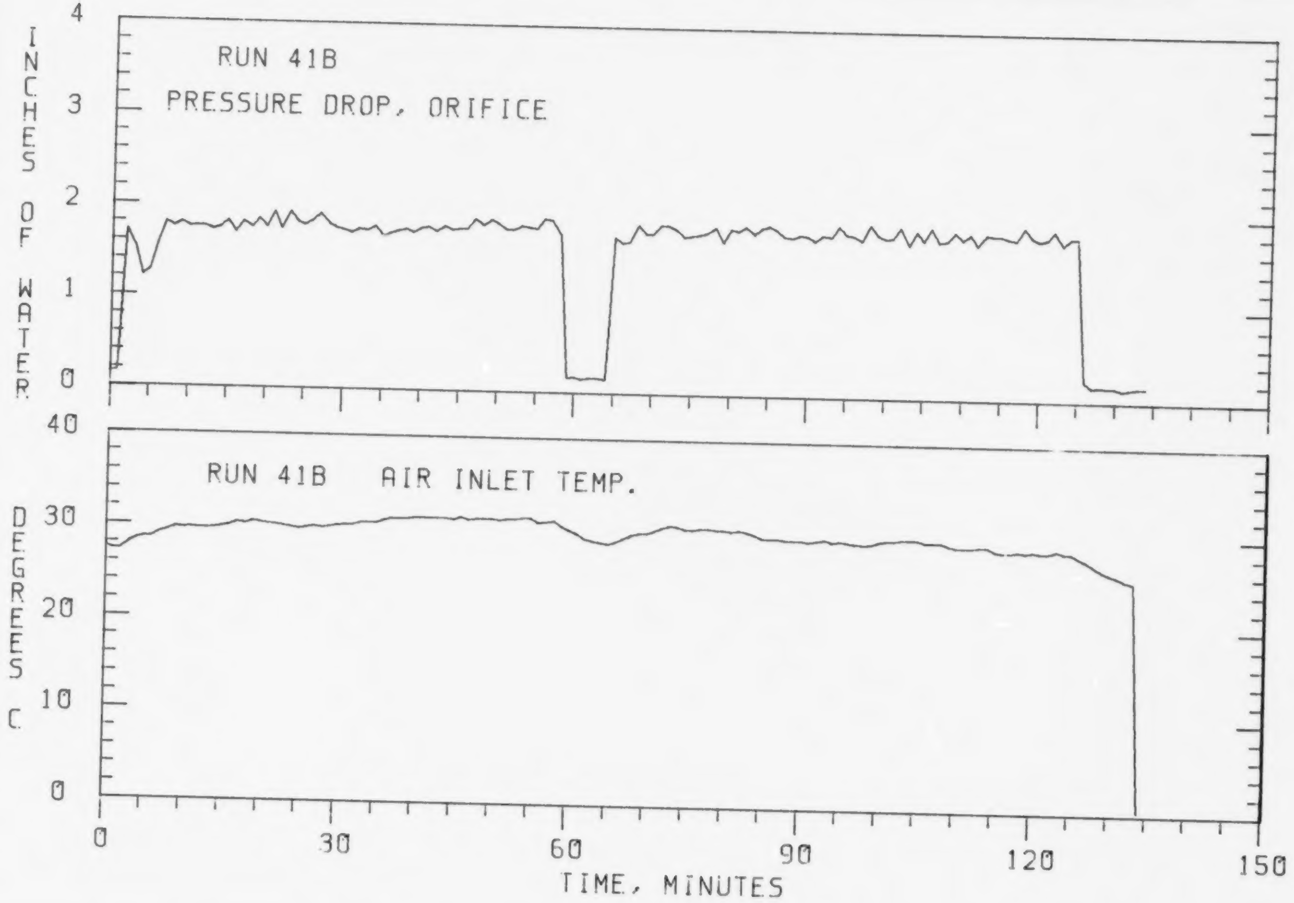

Figure D-21. Air inlet orifice plate pressure drop, air inlet temperature variations throughout Run 41B.

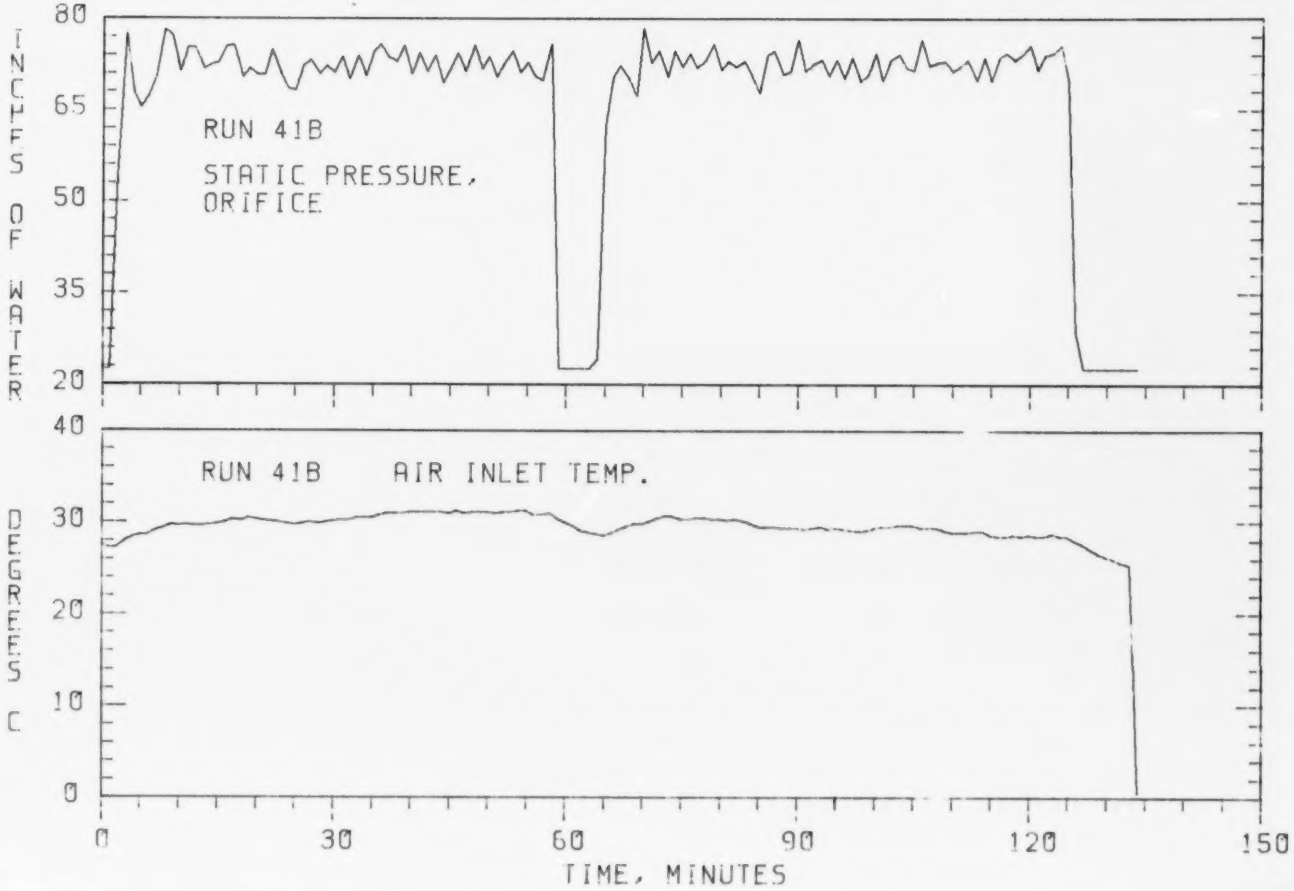

Figure D-22. Air inlet static pressure, air inlet temperature variations throughout Run 41B.

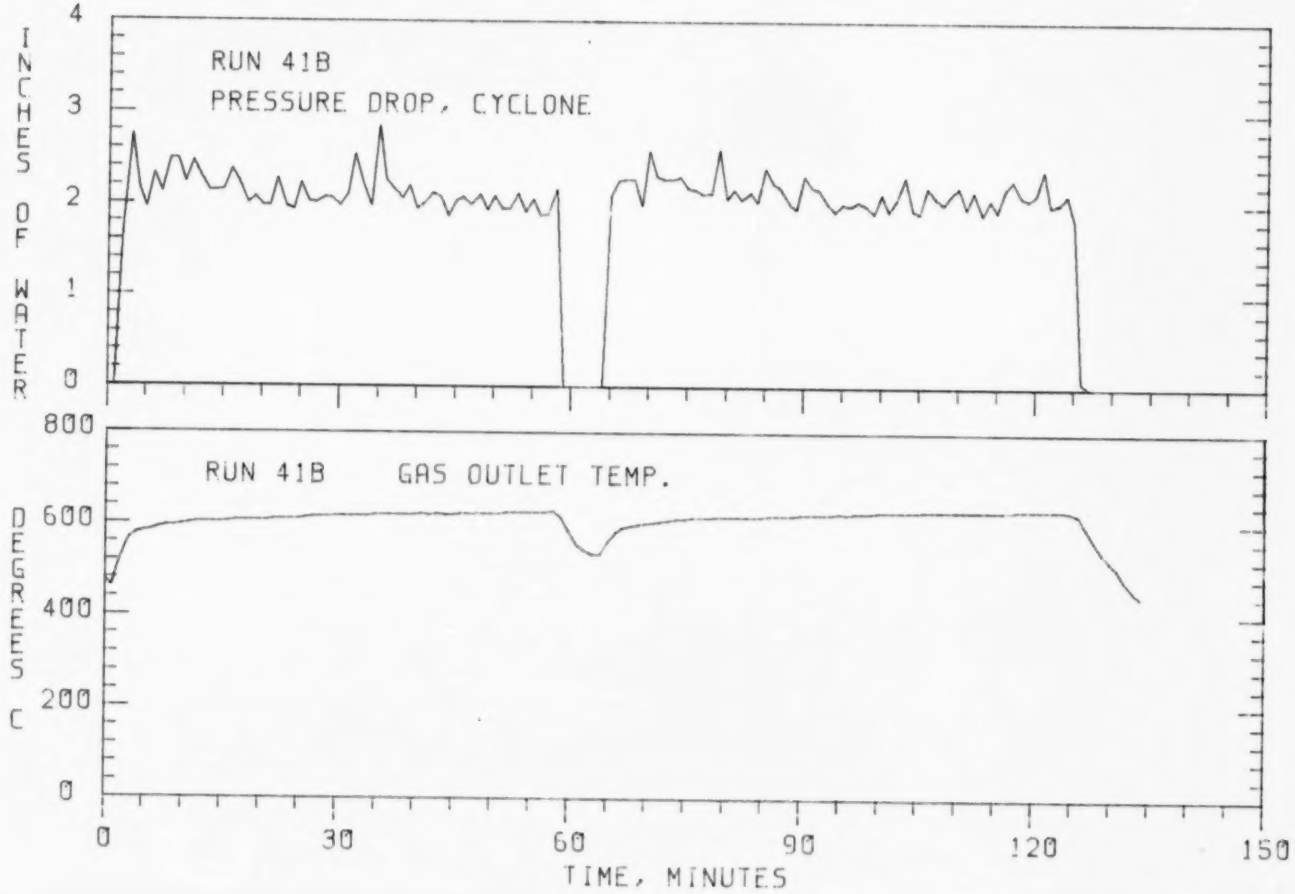

Figure D-23. High efficiency cyclone pressure drop, gas outlet temperature variations throughout Run 41B.

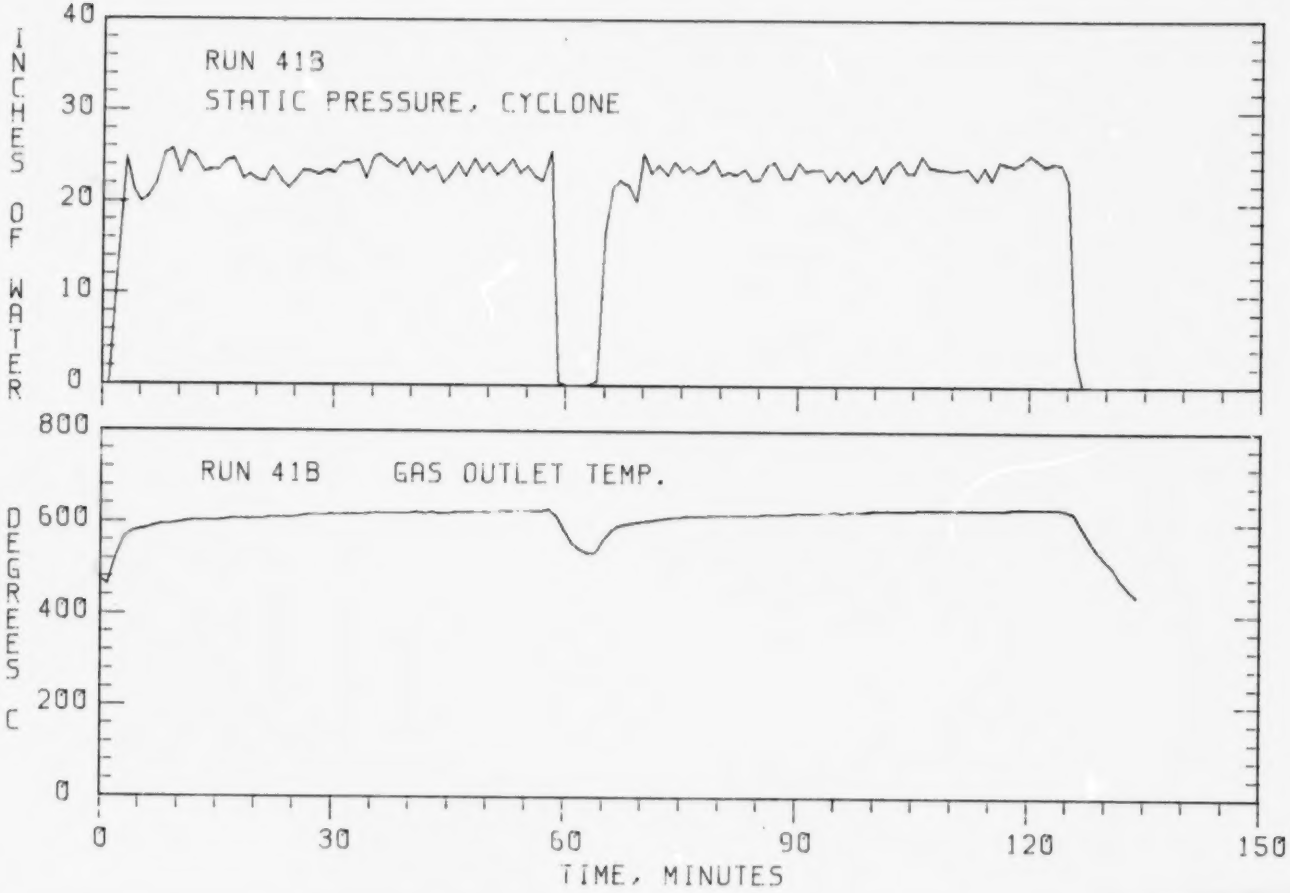

Figure D-24. Gas outlet static pressure, gas outlet temperature variations throughout Run 41B.

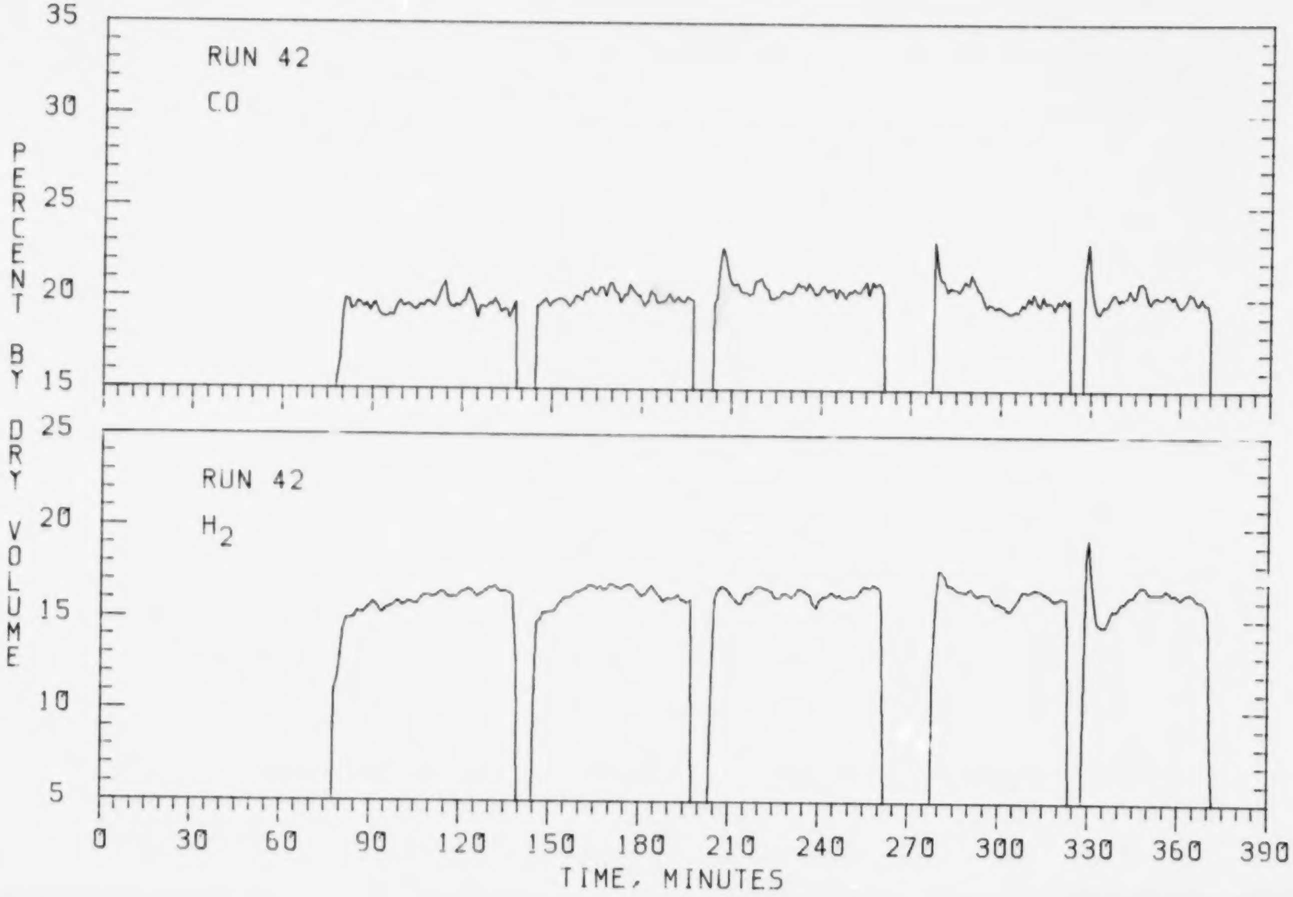

Figure D-25. CO and H_2 concentration variations throughout Run 42.

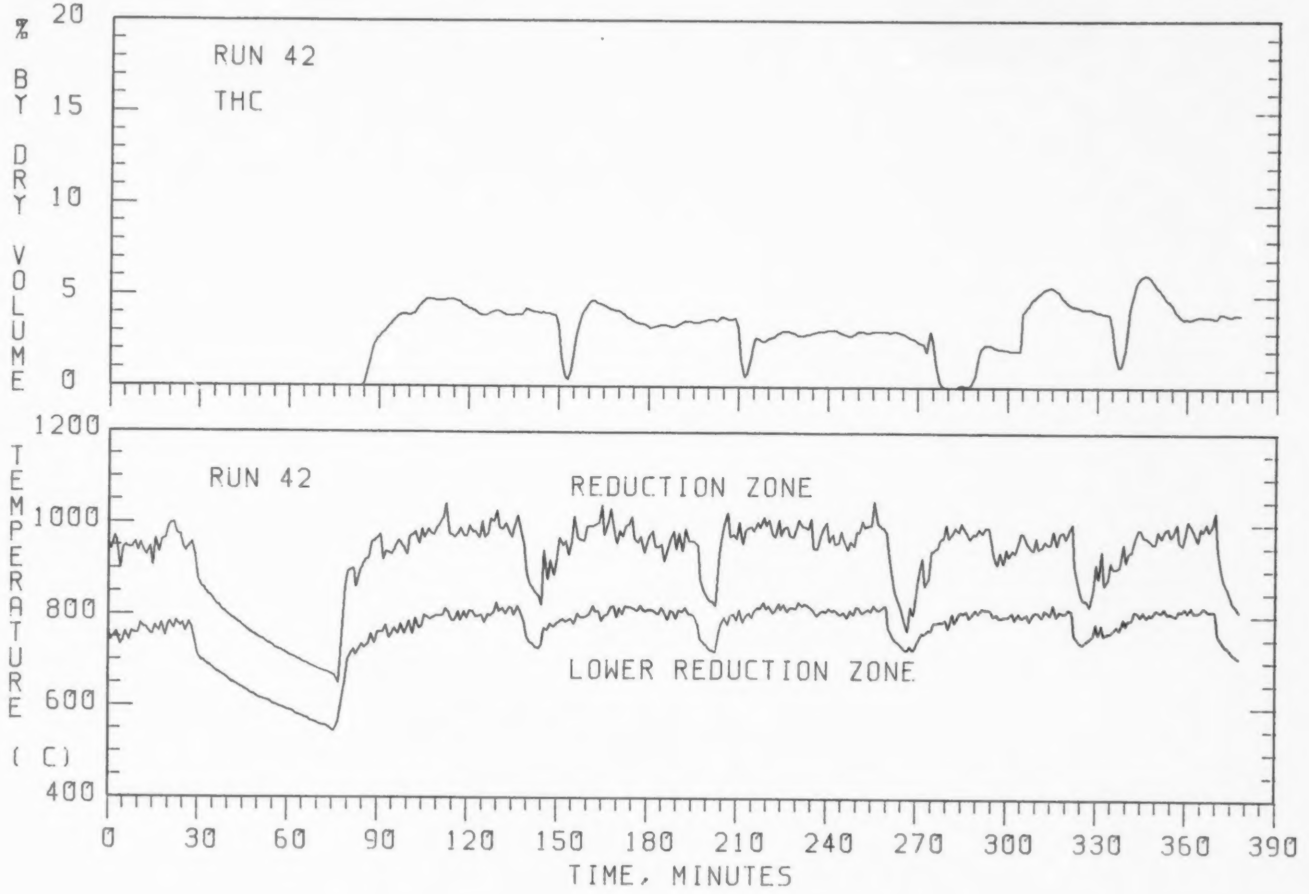

Figure D-26. THC concentration, reduction zone and lower reduction zone temperature variations throughout Run 42.

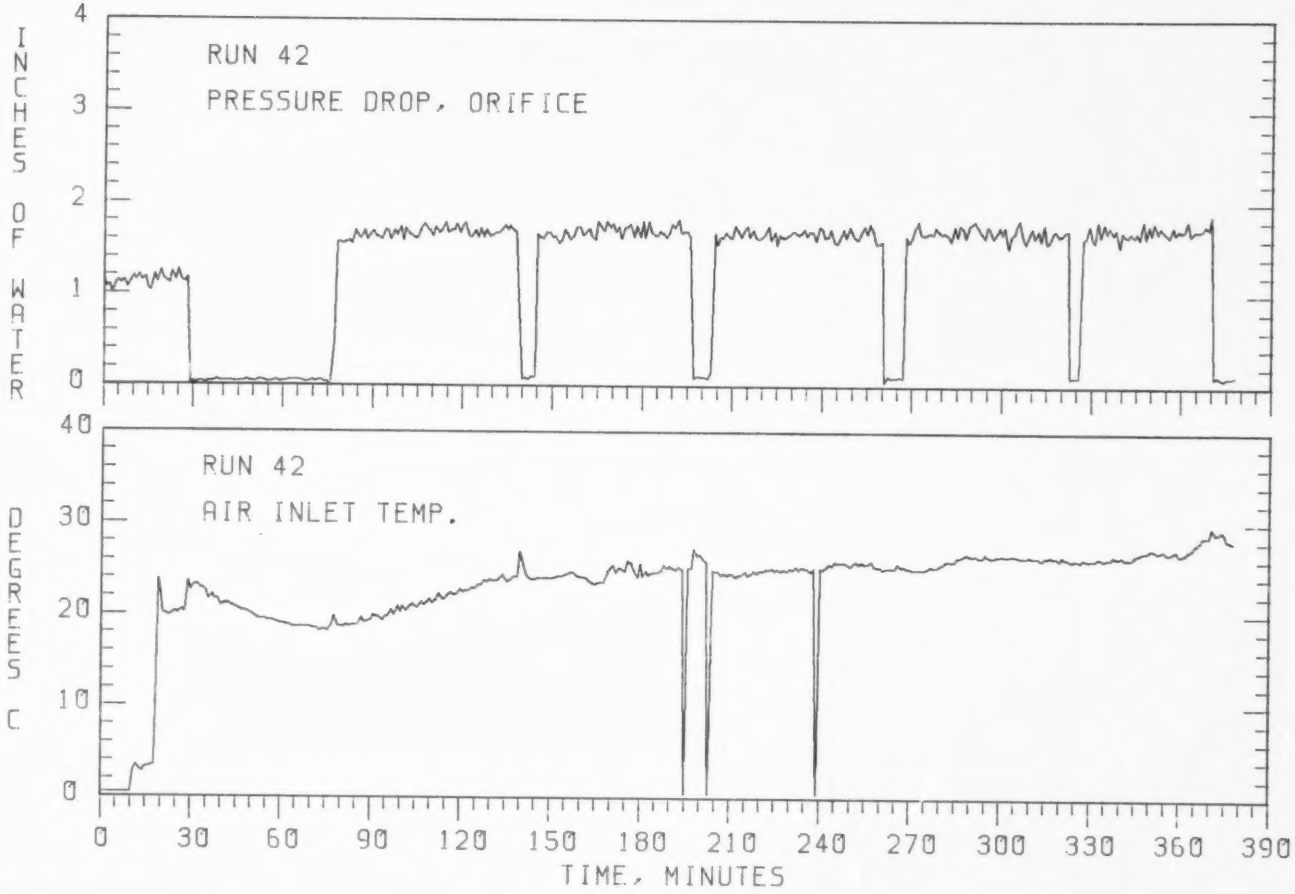

Figure D-27. Air inlet orifice plate pressure drop, air inlet temperature variations throughout Run 42.

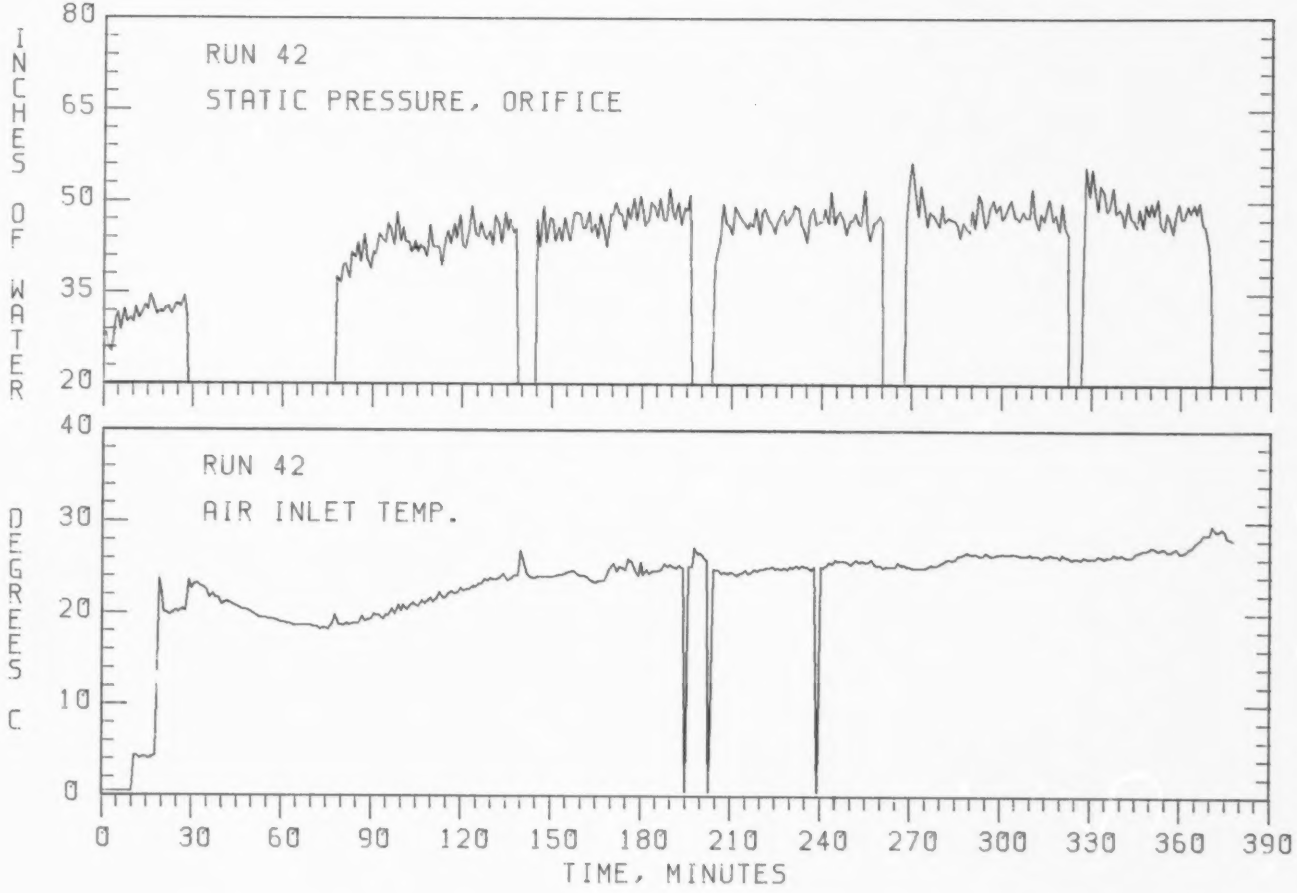

Figure D-28. Air inlet static pressure, air inlet temperature variations throughout Run 42.

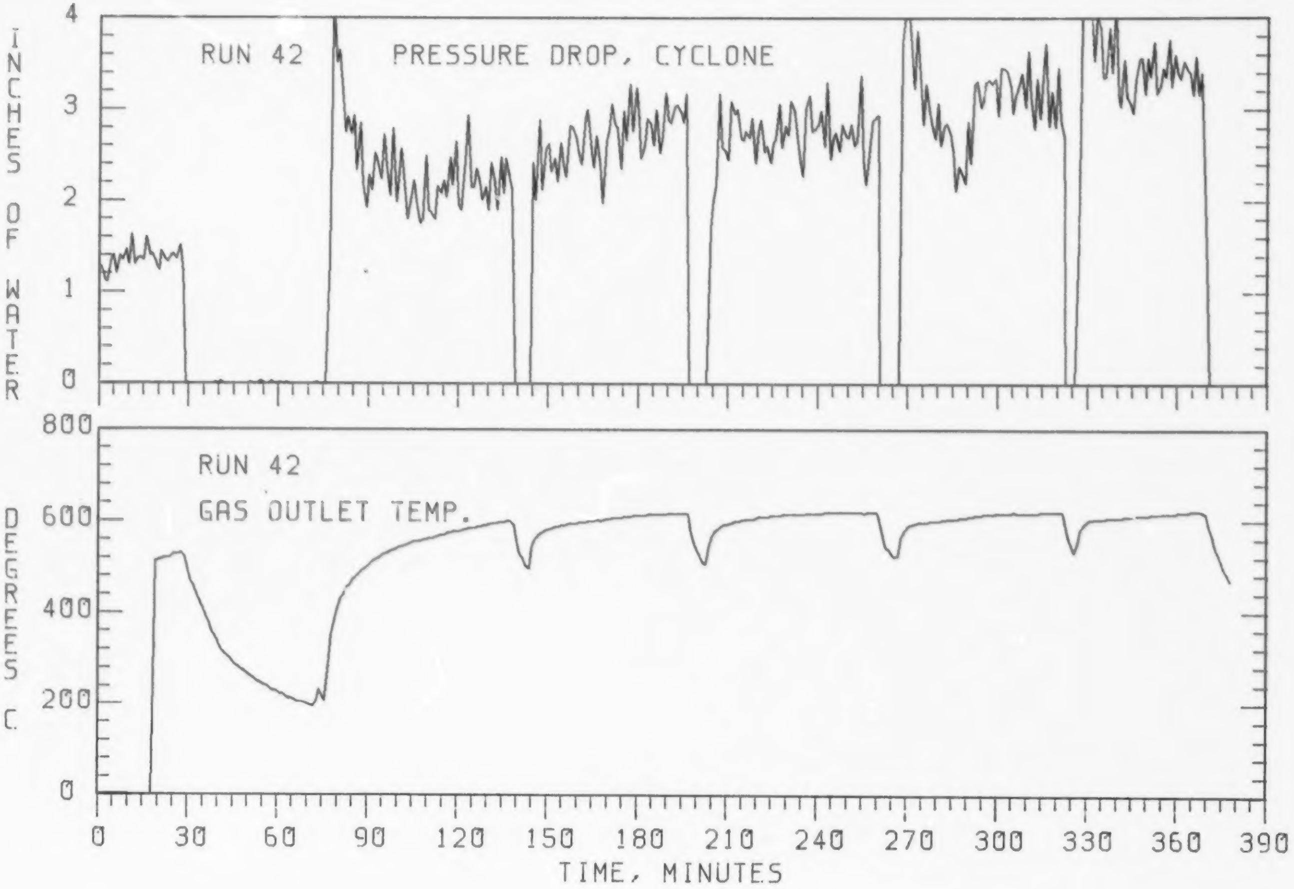

Figure D-29. High efficiency cyclone pressure drop, gas outlet temperature variations throughout Run 42.

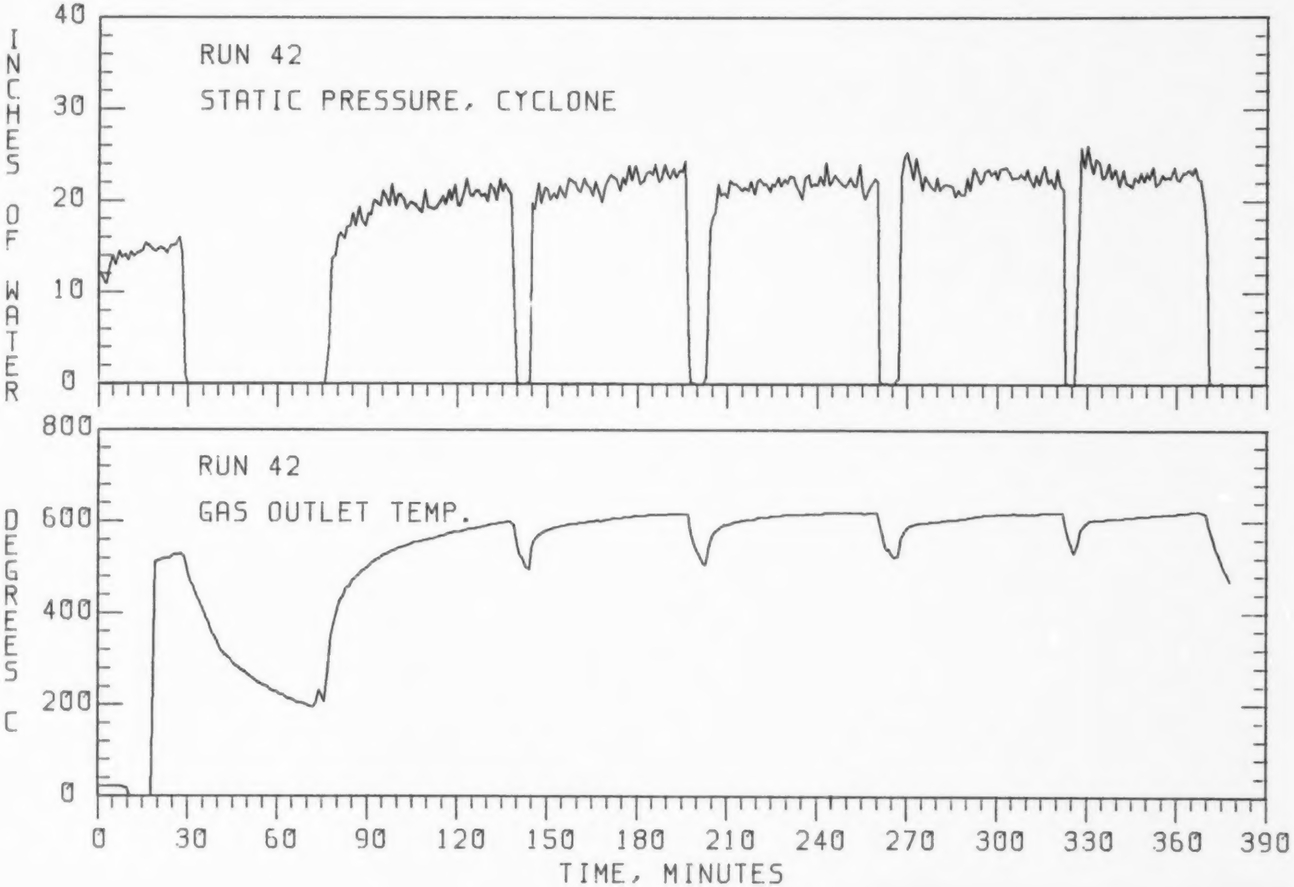

Figure D-30. Gas outlet static pressure, gas outlet temperature variations throughout Run 42.

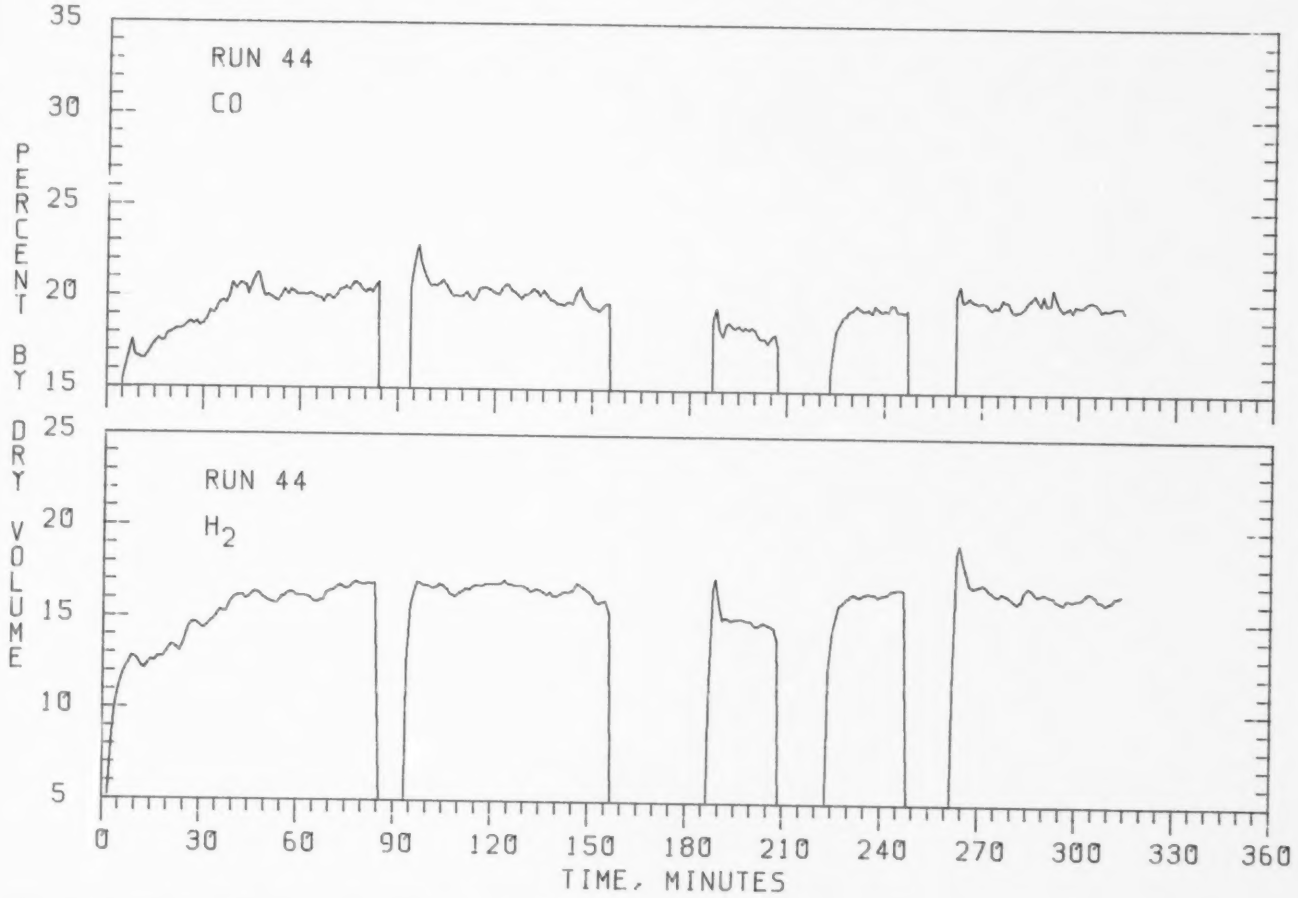

Figure D-31. CO and H_2 concentration variations throughout Run 44.

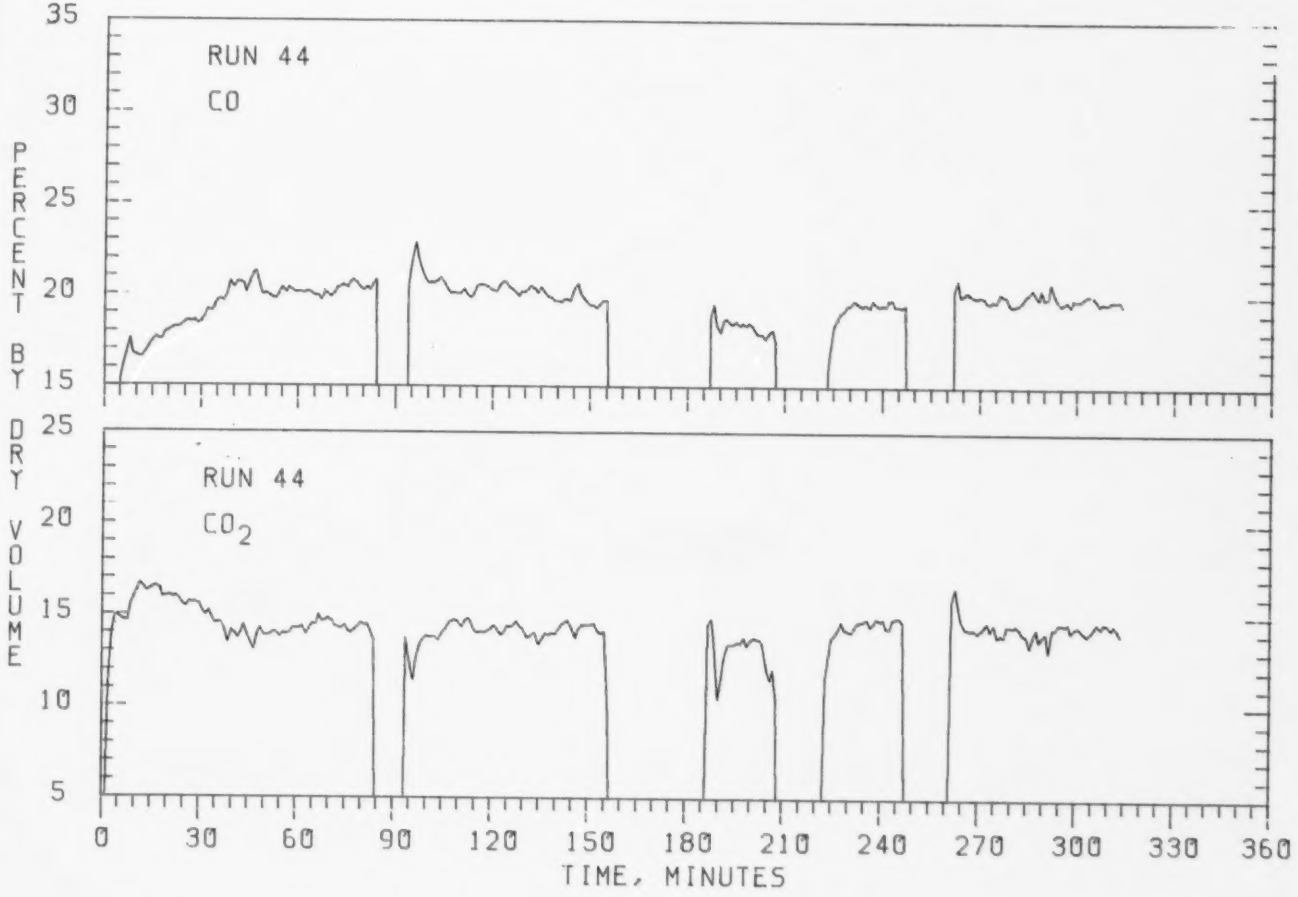

Figure D-32. CO and CO_2 concentration variations throughout Run 44.

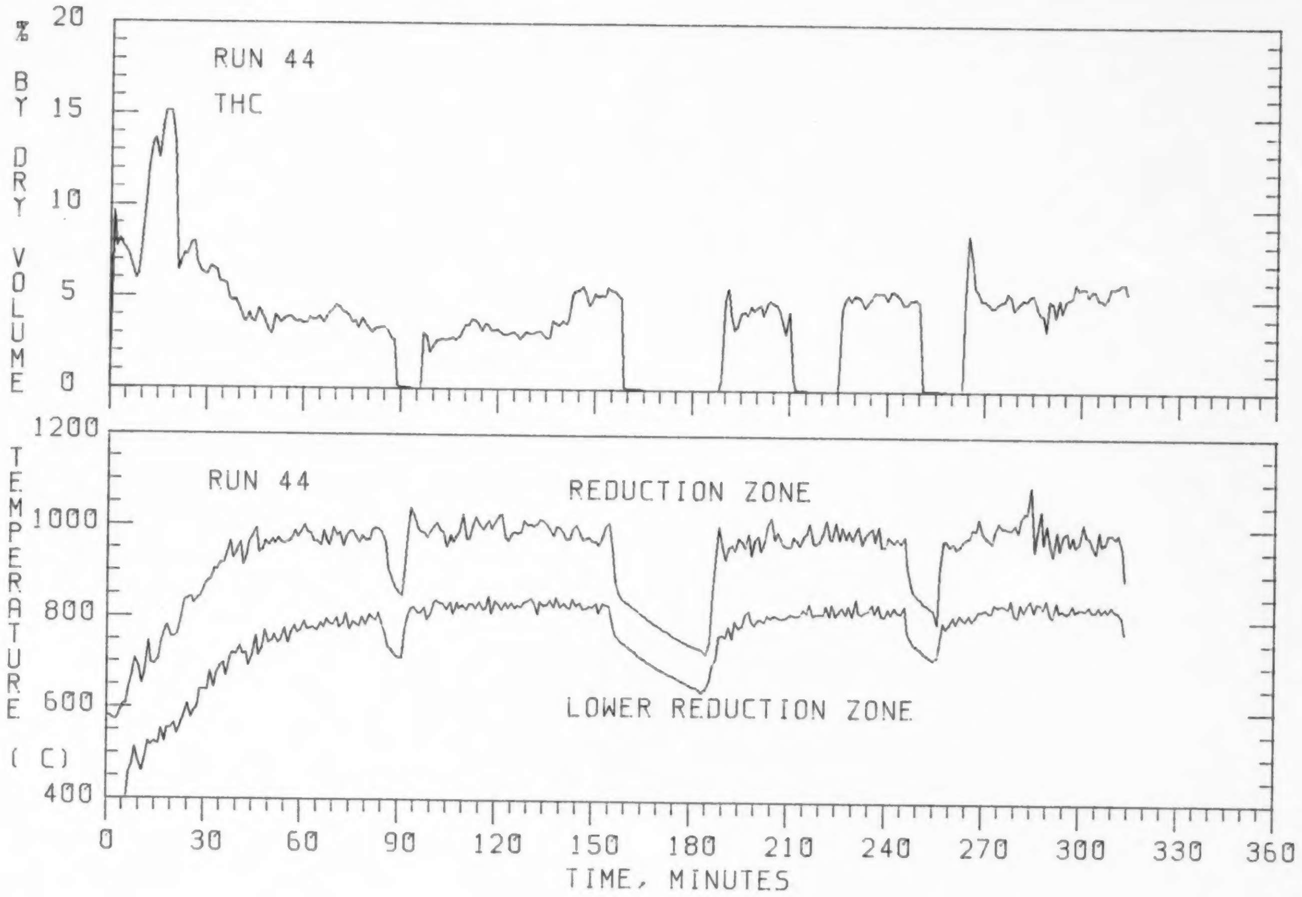

Figure D-33. THC concentration, reduction zone and lower reduction zone temperature variations throughout Run 44.

APPENDIX E

METALS MASS BALANCE RESULTS

Table E-1

CADMIUM MASS BALANCE RESULTS

Stream	Concentrations and percentages of cadmium for each gasifier run						
	40	36	41	37	42	33	38
Fuel, ppm[a]	2.05	2.40		3.20		4.85	
Char, ppm	2.98	3.53	3.98	3.10	3.97	5.40	4.00
% total[b]	22.2	20.6	25.0	15.8	20.5	17.0	13.0
Fly ash, ppm	29.0	22.0	21.6	26.0	27.8	80.2	58.0
% total	11.4	4.5	6.0	6.5	6.9	4.7	10.5
Slag, ppm	5.20	2.30	5.70	4.70	6.20	8.30	3.30
% total	0.2	0.2	nd	nd	0.2	1.7	0.2
Emissions, $\mu g/m^3$	70.2	58.9	69.0	135.	94.0	82.2	136.
% total	61.9	42.8	44.5	88.0	51.2	45.5	52.2
Total cadmium recovered, %	95.7	68.1	75.5	110.3	78.8	68.9	75.9

Table E-2

LEAD MASS BALANCE RESULTS

Stream	Concentrations and percentages of lead for each gasifier run						
	40	36	41	37	42	33	38
Fuel, ppm	37.2	38.3		49.4		80.3	
Char, ppm	132.	105.	107.	128.	114.	132.	163.
% total	54.3	38.5	43.0	42.3	38.2	24.9	32.0
Fly ash, ppm	564.	502.	432.	560.	536.	1690	1040
% total	12.2	6.4	7.7	9.1	8.6	6.1	11.4
Slag, ppm	89.7	72.0	82.3	79.0	82.0	97.5	104.
% total	<0.1	0.4	0.2	0.2	0.2	1.0	0.4
Emissions, μ g/m^3	721.	653.	747.	964.	1000	1260	1380
% total	35.0	29.8	30.8	40.7	35.3	36.4	32.0
Total lead recovered, %	101.5	75.1	81.7	92.3	82.3	68.4	75.8

Table E-3

ZINC MASS BALANCE RESULTS

Stream	Concentrations and percentages of zinc for each gasifier run						
	40	36	41	37	42	33	38
Fuel, ppm	207.	209.		278.		364.	
Char, ppm	749.	672.	657.	818.	817.	943.	1220
% total	55.3	45.1	47.4	48.0	51.4	38.2	52.6
Fly ash, ppm	3650	3740	3690	3470	4590	8510	7280
% total	14.2	8.7	11.9	10.0	13.9	6.7	17.6
Slag, ppm	349.	151.	261.	274.	218.	304.	531
% total	0.1	0.1	0.1	0.1	0.1	0.8	0.6
Emissions, $\mu g/m^3$	2660	2180	2510	3060	3430	3720	3060
% total	23.8	18.2	18.6	23.0	22.7	23.7	15.6
Total zinc recovered, %	93.4	72.1	78.0	81.1	88.1	69.4	86.4

Table E-4

NICKEL MASS BALANCE RESULTS

Stream	Concentrations and percentages of nickel for each gasifier run						
	40	36	41	37	42	33	38
Fuel, ppm	21.6	28.2		33.7		80.7	
Char, ppm	182.	119.	233.	203.	331.	290.	227.
% total	129..0	59.2	124.7	98.2	162.4	54.4	44.3
Fly ash, ppm	184.	105.	271.	153.	357.	334.	188.
% total	6.8	1.8	6.5	3.7	8.4	1.2	2.0
Slag, ppm	453.	366.	669.	361.	671.	384.	363.
% total	1.6	2.6	1.7	1.4	2.9	4.6	1.8
Emissions, μ gm/m^3	124.	54.3	136.	231.0	355.	1180	24.7
% total	10.4	3.4	7.5	143.0	18.4	33.9	0.6
Total nickel recovered, %	147.8	67.0	140.4	246.3	192.1	94.1	48.7

Table E-5

COPPER MASS BALANCE RESULTS

Stream	Concentrations and percentages of copper for each gasifier run						
	40	36	41	37	42	33	38
Fuel, ppm	109.	121.		147.		200.	
Char, ppm	696.	792.	745.	926.	933.	1020	1120
% total	97.6	91.8	92.9	102.7	104.9	77.0	92.2
Fly ash, ppm	716.	750.	659.	680.	754.	1380	1200
% total	5.3	3.0	3.7	3.7	4.1	2.0	4.7
Slag, ppm	1660	1310	4400	1390	1460	1800	1880
% total	1.1	5.3	2.6	1.2	1.4	8.8	1.4
Emissions, μ g/m^3	84.0	65.9	104.	216.	154.	398.	81.0
% total	1.4	1.0	1.3	3.1	1.8	4.6	0.8
Total copper recovered, %	105.4	101.1	100.5	110.7	112.2	92.4	99.1

Table E-6

CHROMIUM MASS BALANCE RESULTS

Stream	Concentrations and percentages of chromium for each gasifier run						
	40	36	41	37	42	33	38
Fuel, ppm	108.	136.		168.		255.	
Char, ppm	566.	716.	728.	988.	904.	1040	1080
% total	80.1	73.9	80.8	95.9	89.0	61.8	66.6
Fly ash, ppm	426.	337.	471.	553.	416.	740.	520.
% total	3.2	1.2	2.3	2.7	2.0	0.9	1.8
Slag, ppm	1190	877.	1330	1640	946.	1200	1100
% total	0.9	1.3	0.7	1.3	0.8	4.6	1.7
Emissions, μ g/m^3	132.	74.9	60.1	189.	93.0	321.	53.2
% total	2.2	1.0	0.7	2.4	1.0	2.9	0.4
Total chromium recovered, %	86.4	77.4	84.5	102.3	92.8	70.2	70.5

Table E-7

IRON MASS BALANCE RESULTS

Stream	Concentrations and percentages of iron for each gasifier run						
	40	36	41	37	42	33	38
Fuel, ppm	2500	2870		3690		5160	
Char, ppt	15.4	21.5	19.4	25.1	23.9	24.2	27.4
% total	96.9	105.1	102.0	110.9	107.1	71.0	83.5
Fly ash, ppt	21.8	22.2	22.5	31.8	23.2	26.6	27.6
% total	7.0	3.8	5.3	6.9	5.0	1.5	4.7
Slag, ppt	47.0	46.2	48.2	49.2	49.2	51.0	47.5
% total	1.5	3.2	1.2	1.7	1.9	9.6	3.6
Emissions, μ g/m^3	2850	6700	1260	4140	2120	9090	1750
% total	2.0	4.0	0.7	2.3	1.0	4.0	0.6
Total iron recovered, %	107.4	116.1	109.2	121.8	115.0	86.1	92.4

ppt = parts per thousand

Table E-8

DISTRIBUTION OF CADMIUM BASED ON EPA METHOD 5 TESTS RESULTS

Location	Percent of total emissions for each run						
	40	36	41	37	42	33	38
Before filter,	7.0	2.7	12.7	22.2	17.0	25.0	0.7
Filter,	92.3	97.3	87.0	77.8	83.0	52.3	99.3
After Filter	0.7	nd	0.3	nd	nd	22.7	nd

nd = not detectable

Table E-9

DISTRIBUTION OF LEAD BASED ON EPA METHOD 5 TEST RESULTS

Location	Percent of total emissions for each run						
	40	36	41	37	42	33	38
Before filter,	4.0	0.9	3.2	5.7	4.3	7.9	0.4
Filter,	96.0	99.1	96.8	94.3	95.7	78.3	99.6
After filter,	nd	nd	nd	nd	nd	13.8	nd

nd = not detectable

Table E-10

DISTRIBUTION OF ZINC BASED ON EPA METHOD 5 TEST RESULTS

Location	Percent of total emissions for each run						
	40	36	41	37	42	33	38
Before filter,	11.7	2.2	12.7	17.2	16.5	14.0	0.6
Filter,	87.1	97.8	84.5	82.8	83.5	64.0	99.4
After filter,	1.2	nd	2.8	nd	nd	22.0	nd

nd = not detectable

Table E-11

DISTRIBUTION OF NICKEL BASED ON EPA METHOD 5 TEST RESULTS

Location	Percent of total emissions for each run						
	40	36	41	37	42	33	38
Before filter,	77.0	59.3	17.7		90.1	46.7	40.1
Filter,	23.0	40.7	82.4		9.9	0.4	59.9
After filter,	nd	nd	nd		nd	52.9	nd

nd = not detectable

Table E-12

DISTRIBUTION OF COPPER BASED ON EPA METHOD 5 TEST RESULTS

Location	Percent of total emissions for each run						
	40	36	41	37	42	33	38
Before filter,	26.7	18.8	48.1	70.4	56.3	5.3	5.1
Filter	62.6	81.2	51.9	29.6	43.7	12.5	94.9
After filter,	10.7	nd	nd	nd	nd	82.2	nd

nd = not detectable

Table E-13

DISTRIBUTION OF COPPER BASED ON EPA METHOD 5 TEST RESULTS

Location	Percent of total emissions for each run						
	40	36	41	37	42	33	38
Before filter,	26.7	18.8	48.1	70.4	56.3	5.3	5.1
Filter,	62.6	81.2	51.9	29.6	43.7	12.5	94.9
After filter,	10.7	nd	nd	nd	nd	82.2	nd

nd = not detectable

Table E-14

DISTRIBUTION OF CHROMIUM BASED ON EPA METHOD 5 TEST RESULTS

Location	Percent of total emissions for each run						
	40	36	41	37	42	33	38
Before filter,	45.0	8.0	24.6	66.4	44.6	16.5	10.0
Filter,	55.0	83.4	56.6	33.6	55.4	6.2	90.0
After filter,	nd	8.6	18.8	nd	nd	77.3	nd

nd = not detectable

Table E-15

DISTRIBUTION OF IRON BASED ON EPA METHOD 5 TEST RESULTS

Location	Percent of total emissions for each run						
	40	36	41	37	42	33	38
Before filter,	8.7	2.6	8.6	6.1	13.8	7.1	3.1
Filter,	91.3	86.8	87.7	93.9	84.2	67.2	96.9
After filter,	nd	10.5	3.7	nd	2.0	25.7	nd

nd = not detectable